ADAPTING ARCHITECTURAL FORM OF RESIDENTIAL BUILDINGS IN HOT CLIMATES: TWO CASE STUDIES FROM MUSCAT, OMAN

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ABSTRACT: The discourse on energy-efficient buildings tends to shift out of the realm of architecture and into engineering and programming. In the latter disciplines, sophisticated solutions are always being developed and introduced to the green building industry. However, such solutions require financial and technical capacities that are only found in technologically highly developed countries. In developing countries and their ever-growing metropolises, a much more robust approach seems appropriate. This paper explores how the energy demand for creating comfortable interior environments in very hot climates can be significantly reduced by promoting straightforward architectural means. It seeks to relocate the discourse back into the realm of design, where less costly, more feasible, and long-lasting solutions can be found. The paper presents two case studies of residential architecture in Muscat, Oman. Through simulations of solar insolation as well as daylight studies, it shows how architectural form can respond to two solar phenomena - heat and light – in such a way that insolation on glazed facades is minimized, while illuminance of interiors is optimized. It claims that this can lead to a new regional architectural idiom that puts the famous modernist credo on its head by stating that energy-efficient buildings in a hot climate zone require "light and air, but no sun".

Keywords: Ventilation; Insolation; Illuminance, Energy-Efficiency, Visual Comfort; Oman

تعديل الشكل المعماري للمباني السكنية في المناخات الحارة: دراستا حالة من مسقط، عمان

نيكولاس نيبل* و هاريندرين باراماهمسا

الملخص: يميل الحديث عن المباني عالية الكفاءة إلى التحول من مجال العمارة إلى مجالات الهندسة والبرمجة، التي تقدم باستمرار حلولا متطورة لصناعة المباني الخضراء، غير أن هذه الحلول تتطلب قدرات مالية وتقنية لا تتوفر إلا في البلدان المتقدمة تقنيا، بينما يبدو اتباع نهج أكثر رصانة مناسبا في البدان النامية وعواصمها المتنامية باستمرار. تستكشف هذه الورقة كيف يمكن أن تقلل الطاقة المستهلكة لخلق بيئات داخلية مريحة في المناخات شديدة الحرارة إلى حد كبير عن طريق وسائل معمارية بسيطة ومباشرة، كما أنها تسعى لإعادة الحديث عن المباني عالية الكفاءة إلى مجال التصميم المعماري، حيث توجد حلول طويلة المدى أقل تكلفة، وأكثر جدوى. تستعرض الورقة دراستي حالة للعمارة السكنية في مسقط في عمان، وتظهر من خلال محاكاة الاشعاع الشمسي الساقط، وضوء النهار، كيف يمكن للشكل المعماري أن يستجيب لظاهرتين شمسيتين – الحرارة والضوء – بطريقة تقلل الاشعاع الشمسي الساقط على الواجهات الزجاجية، في الوقت نفسه الذي يتم فيه تحسين الإضاءة الداخلية. تزعم الورقة أن هذه الطريقة ستؤدي إلى أسلوب معماري إقليمي جديد يقلب التوجه الحداثي، ويعبر عن عمارة عالية الكفاءة في المناخ الحار ترفع شعار "ضوء وهواء، لكن لا شمس!".

الكلمات المفتاحية: التهوية؛ التشمس؛ الإضاءة؛ الراحة الحرارية؛ العمارة، المباني الموفرة للطاقة؛ الضوء.

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1. INTRODUCTION

The development of energy-efficiency of buildings - however late it may be in the race against global warming - is progressing. Yet, it can be observed that this progress tends to take place in the development of more and more technically sophisticated building components and increasingly automated operations. The field of innovation seems to be in the fields of civil, mechanical, and electrical engineering as well as in programming rather than in architectural design. A poignant example where this tendency is manifested is the prototypical zero-energy buildings that were developed in the framework of the so-called Solar Decathlon competitions over the past decade in Europe, the United States, China, the Middle East, and lately also in Africa (Solar Decathlon, 2020). While these buildings become more and more equipped with smart materials and smart technologies, their architectural designs show limited progress.

This development bears the risk of raising the planning, construction, and operations of energy-efficient buildings to a level of complexity at a time when simplicity is called for. Today, the world is facing a "global air-conditioning surge" (Cox, 2012). This phenomenon describes that the current rapid urban growth that is taking place in the metropolises of the Global South, which are mainly in hot or tropical climates, is coupled with the rapid emergence of middle-class societies and thus growing demand for building cooling systems. However, for the time being, this demand can often only be met by installing outdated and/or oversized mechanical cooling systems and technologies in buildings that are designed and constructed inefficiently. Current practice in Muscat, Oman, for example, is to construct single-leaf concrete blocks without insulation. The problem is that the progress in making buildings more energy-efficient, which is mainly happening in the disciplines of engineering and programming, is outstripping the financial capacities and technological expertise of the markets.

The question raised here is, how much progress towards energy-efficiency of buildings can be achieved through the architecture itself, which may be a technically much simpler discipline than engineering or programming but a very effective means for saving energy through design concepts? All too often, this potential of the discipline of architecture is not used to its full extent. This can be seen on a global scale in the contradiction between the general similarity of contemporary architectural forms versus the variety of climatic conditions.

This paper makes a case for architectural design. It aims to explore how in the early stage of a design process, the shape of a building can be formed with simple means as arranging functions in floor plans and orienting openings in facades so that the basis for energy-efficiency is already laid before the planning process enters into the potentially more cost-intense and high-tech realms of engineering and programming in later stages. This approach to energy efficiency through architectural design is demonstrated in this paper with two case studies of residential buildings in Muscat, Oman. The city is growing rapidly (Statista, 2018), and the already hot climate is bound to increase even more (Pal & Eltahir, 2015). The construction industry operates mainly with unskilled labourers, and the market for innovative technologies seems too small to attract state-of-the-art products and service providers. In this situation, which is representative of many metropolises of the Global South, architectural design can make a significant difference.

When designing a building, the most basic climatic setting is its relation to the sun. The sun is a source of energy, and it radiates heat and light. This dual effect from the same cause poses a particular challenge for the design of an energy-efficient building in a hot climate because the form of a building needs to keep the heat out but let the light in. Or, to formulate it as a design paradox: buildings should be "closed but open" at the same time. Respectively, the building form evolves from a negotiation of the two parameters of insolation and illuminance; both of which can be simulated through local weather data and a digital model of the building's preliminary design and be optimized at an early stage of the planning process, as is done in this study.

This paper connects the issues of energy efficiency and comfort by looking at buildings as artefacts in relation to their urban location and solar geometry and also by conceiving buildings as environments that are perceived by their users. The binding element is the building form. The research questions are thus:

1) Insolation: What are the consequences for building form when under the conditions of intense insolation in hot climates, the heat gains in buildings are minimized through measures on the primary level of architectural design in the early stages of a design process (before a secondary level of material science or civil engineering is even entered)?

2) Illuminance: What are the consequences for building form when under the climatic conditions of a predominantly clear sky with a very high luminance as well as a very high annual amount of sunlight hours, visually comfortable conditions for the indoor environment are pursued?

3) Ventilation: What are the consequences for building form when the periods of natural ventilation through cross-ventilation of all major rooms are enabled through design for the period of passive cooling throughout the year to be prolonged?

Figure 1. Aerial view of a typical suburb in the Western outskirts of Muscat, Oman, showing single-family villas on spacious plots; wide streets, no trees. (Photo by Harindren Paramahamsa).

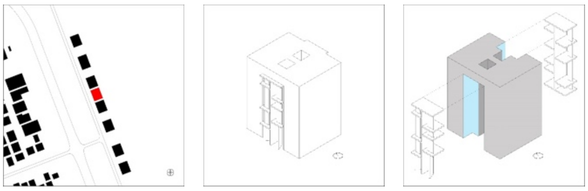

Figure 2. Windtower. figure-ground plan; exploded axonometry 1; exploded axonometry 2. (Illustrations by Authors).

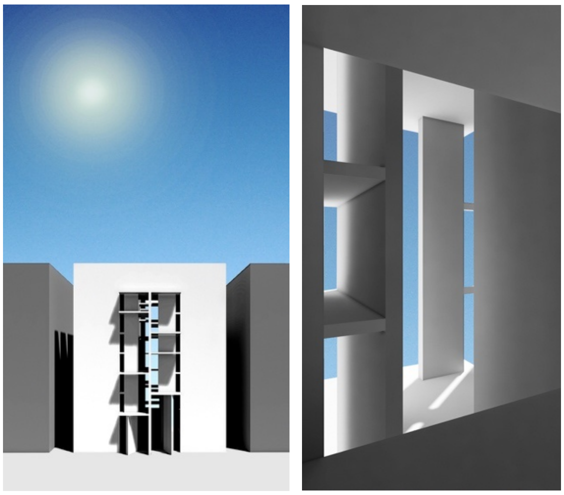

Figure 3. Windtower. rendering of the view from the West, view into the shaded, ventilated outdoor space within the building volume. (Illustrations by Authors).

This paper shows how adaption to climatic conditions - by avoiding insolation on glazed openings, providing comfortable illuminance, and enabling natural ventilation - can lead to designs that are different from the standard practice and can be an inspiration for a new vernacular architectural idiom. The paper first introduces the two designs. It then explains the method of developing these designs with regard to simulations of insolation, solar access as well as illuminance. Finally, it discusses the findings with an outlook on climate-adapted building typologies for this region.

CASES

The two case studies of this paper are designed for residential architecture in Muscat, Oman; by coincidence, they are located in the same suburb, Al Khoud. One is a multi-unit tower, and the other is a single-family villa, both of which stand for the predominant building typologies of the urban fabric (Figure 1). Hence, beyond the individual cases, the design solutions as well as the research findings from this paper will be transferrable to other design tasks and will have a general value for the discourse on energy-efficient buildings in this city and climate.

Case One – Windtower

The Windtower project is located on a 500m^2 plot with a side length of 25m by 20m and is part of a linear row of several such units. Building regulations as defined in the title deed ("krooki") allow for full coverage of the plot (Built Area Ratio = 1,0), a height of nine stories ("G+8"), and a mix of commercial and residential use. The plot is oriented such that the longer sides face open spaces; towards a very broad street in front-facing south-west and towards a wide-open field at the back facing northeast. The northwest and southeast sides face adjacent buildings of the same volume, which stand at a distance of only 5m (Figs 2, 3).

The design (Figs. 2, 3) aims at negotiating insolation, illuminance, and ventilation through architectural form. The first decision was to avoid insolation on glazed facades exposed to the sun, which led to the radical closure of the elevations facing the southwest and northeast facades. To compensate for this, the second decision was to open the centre of the tower and orient all apartments towards this void space to provide illuminance and ventilation. Furthermore, all service spaces are arranged towards the rear, facing adjacent buildings with gaps between them to allow for a second source of daylight as well as cross-ventilation. The vertical circulation is through two cores that are connected by an outdoor bridge in the middle of the tower. On the entrance level to each unit, there is a large terrace that provides a shaded and ventilated outdoor living space. All rooms are simple and spacious rectangles, and through this form, they are functionally neutral. There are two rooms per unit on each floor, and the units can be combined as single-floor, duplex, or triplex apartments. The plans are based on a modular grid, and the construction could easily be implemented with prefabricated construction elements.

In this design, simplicity is key. While the basic layout is clear, simple, and similar in all four quadrants of the tower, the two main facades are designed differently in order to adjust precisely to the solar orientation. However, this is achieved by modifying only one architectural element. This element is a segment of the enclosing wall that is moved to the ideal position to keep sunlight from directly hitting the windows for most of the day while letting the breeze come through. On the ground floor towards the street side, these wall segments are turned outwards to create an entrance gesture and tension by introducing an irregularity in the otherwise relatively regular composition of the facade.

Case One – Umbrellahouse

The Umbrellahouse is located on a rectangular 23m by 50m plot and has an area of 1,150 sqm. It is within an area of similar such plots on which free-standing, two-storey villas are built. The building regulations, as stated in the title deed ("krooki"), define setbacks from the plot boundary of 8m in front, 2m on the sides, and 5m at the back and allow a maximum building height of 8m. The rectangular plot is oriented at a 30° angle along its longer dimension to the northeast (Figs. 4 and 5).

The design's (Figs. 4 and 5) goal is to balance between light, air, and sun through architectural form. The first decision that was taken was to put all private living areas of the villa on one level and to elevate this main volume of the building to create a shaded garden. The 'public' area of the house – mainly the Arab reception room called majlis – remains in a smaller volume on the ground floor and has a view to both sides of the garden. The second decision was to keep all outer facades closed to ensure privacy and avoid insolation on unprotected glazed facades. The third decision was to punctuate the upper volume with light yards, which are also the main elements that structure the spaces. On the one side, a large circular yard is set within the square volume of the living room, creating a continuum of different zones – an open kitchen, play areas, dining, and living room (see floor plan in Figure 11). On the other side, two narrow yards divide each pair of the four bedrooms and provide light along the long sides of these spaces. In both yards, there are small terraces that enhance the connection between the garden and the living spaces above it.

To underline the aim of simplicity, only one architectural element of this design is used for negotiating the issues of insolation versus illuminance. In this case, it is the openings of the roof slab over the yards and their dimensions and positionings. For the long and narrow yards, the openings are set at a third of the yard's width, which will keep almost all direct sunlight off the glazed facades and yet provide ample daylight. Over the large round courtyard, the opening is an oval that is turned with its long axis into exact northsouth orientation and the short axis in the east-west direction. This creates wider roof cantilevers to keep out the flat sun in the mornings and afternoons, and a shorter one to prevent the higher sun at noon from hitting the glazed facades (Figs 4, 5).

3. METHODS

The projects are in an early stage of the design process and therefore this research was carried out through simulations with a digital model. Since the designs call for simplicity, the same approach was applied for the simulation and evaluation method. It was decided to use only one CAD programme, Autodesk Revit 2019 (v19.0.1.1) with its corresponding Autodesk Insight Add-in 2019 (v4043), a Building Information Modelling (BIM) software, through which an integrated design process is enabled, which means that direct feedback between design iterations and simulation results is possible. Revit is widely used in the professional as well as the educational realm of architecture, and thus the steps demonstrated here can be replicated by students and practitioners.

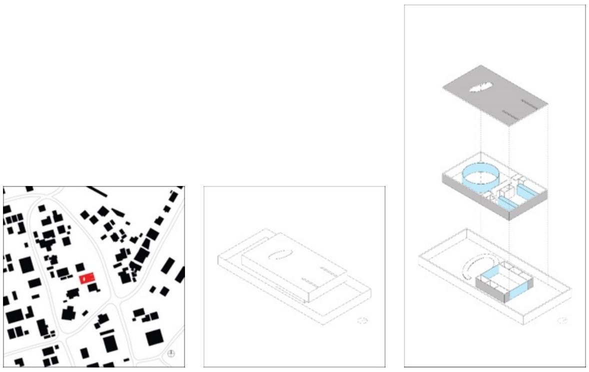

Figure. 4. Umbrellahouse. figure-ground plan; exploded axonometry 1 facing the street side towards the East; exploded axonometry 2; rendering. (Illustrations by Authors).

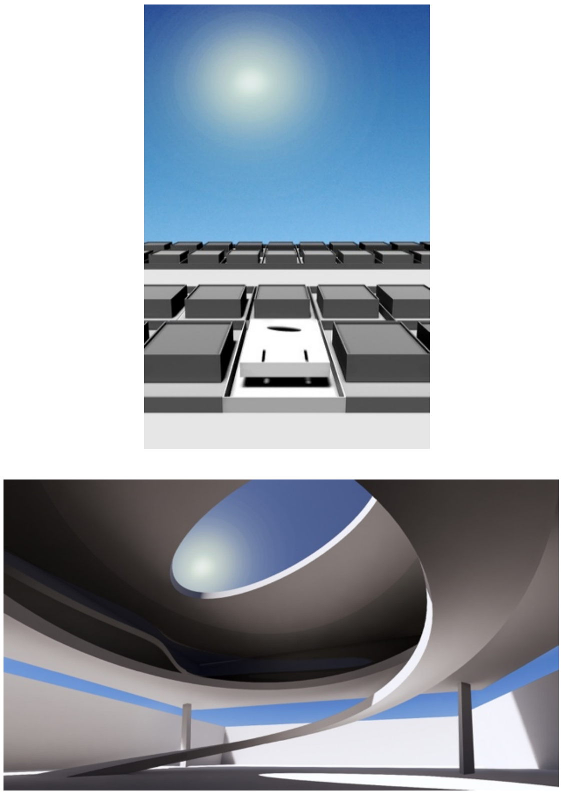

Figure 5. Umbrellahouse. rendering of the view from the East, view into the shaded and ventilated outdoor space under the building volume. (Illustrations by Authors).

Input Data
Simulations of insolation, as well as illuminance, require local weather data. In Revit, this data is available through a link to the databank of the World Meteorology Organization (WMO). For this study, the data from a weather station located within a range of less than 10km from the sites of the two case studies were selected (Autodesk Revit Weather Data, 2020).

Digital Model
The digital model was built with only the minimal required specifications to emphasize the desire for simplicity at this early stage of the design process. To study insolation as well as illuminance, the important question to answer is: which building elements are solid/opaque and which are transparent/glazed. For the opaque building elements, the structural strength or thermal capacity of the material is not yet relevant at this stage and is thus not defined further. However, what needs to be defined is the Light Reflectance Value (LRV) of the surfaces of the building elements. To limit the specifications to this one factor, the authors defined a new material in the Revit materials library, which is actually a "non-material" because it has no other specifications than a Light Reflectance Value that is expressed through equivalent colour values (RGB) - an option that is offered in the Revit settings (Autodesk Revit Reflectivity Settings for Materials, 2020). Further, to deliberately stay away from any detailed design decisions, the reflectance for the different surfaces within the rooms, the standard settings from LEED analyses were carried over (LEED v4, 2019). Thus, the specifications for the Light Reflectance Value throughout both projects are walls 50%, floors 20%, and ceilings 80%, respectively. For the glazed building elements, the specifications are kept equally simple. Since neither the frame and glass qualities nor other factors, e.g., the Solar Heat Gain Coefficient (SHGC), is important at this early stage of the design process, the windows were modelled simply as 100% transparent walls.

Further, it needs to be noted that in the digital models of the two case studies, the urban contexts of the plots were treated differently. While for the Windtower, the mutual shading effect from the adjacent buildings was taken into consideration, this was not done for the Umbrellahouse, which was modelled without neighbouring buildings. Their effect on the result was deemed negligible because it would affect only a small portion of the facade, which is without glazed openings.

Simulated Parameters
Different simulations were needed to find an optimal balance between minimal heat gains through glazed openings as a precondition for energy-efficiency and sufficient daylighting as a condition for visual comfort. They were carried out and set in relation to each other: accumulated insolation on the opaque and glazed facades and solar access in addition to illuminance levels in the rooms of the buildings.

Accumulated Insolation
The parameter insolation describes the energy per unit area that is received from the sun on a particular surface and is cumulated over a time interval. The unit of insolation is kWh/m^2. For the analysis of the insolation, the relevant input data is the Global Horizontal Irradiance (GHI) that sums up the direct and diffuse horizontal irradiance from the sun on a horizontal surface. In this study, the given GHI data for the specific location that is pre-set in Revit was used.

Since the focus of the analysis in this paper is to compare the insolation on opaque as well as on glazed facades only vertical building elements - walls and windows - and not horizontal elements - roof and floors - were selected for the evaluation. And since the aim is to link the analyses of insolation and illuminance, a decision about whether to measure at a specific point in time or over a period of time had to be taken. Since the illuminance analysis is often, e.g., in LEED, set to three representative days for significantly different solar situations (Jun 21, Sep 21, Dec 21) as well as a morning and an afternoon time as a representative of one day (9:00 a.m. and 3:00 p.m.). It was decided to simulate the insolation on the same specific days, however, not as a peak or average insolation, but as accumulated insolation for the time from sunrise to sunset. In this way, the strategies for reducing heat gains to create energy efficiency and the strategies for mediating daylight to create visual comfort can be assessed in relation to each other.

Solar Access
A solar access study is a means to analyze which areas in a building receive direct sunlight during a defined period of time and within defined time intervals. The latter issue, the accumulation of measurements over a period of time, makes it different from a shading study that only features a particular point in time. In this study, we look at the duration of one day (6:00 a.m. – 6:00 p.m.) on the specific days that were defined to be representative for each season (Jun 21, Sep 21, Dec 21). While in temperate climate zones solar access studies are used to ensure that rooms in buildings have a minimum of direct sunlight as a means of comfort, this is different in hot climate zones like Muscat. Here, the aim is to avoid direct sunlight in rooms of buildings, and thus in this case the defined threshold within a solar access study is to be set at a maximum time value (e.g. one or two hours) in order to achieve thermal and visual comfort as well as energy-efficiency. For the design development of the case studies presented in this paper, the solar access study was used to fine-tune the shape of the architectural elements that block the sun from the glazed facades.

Illuminance
The parameter illuminance describes the total

luminous flux incident on a surface per unit area (REF) at a defined point in time. The unit of illuminance is lux (lx). The analysis of the illuminance requires setting the input data about the luminance of the sky appropriately for the location. The important factors are the daylight hours and the cloudiness of the sky. Daylight hours are the period between sunrise and sunset at the horizon during which natural illumination of the environment is experienced. In Muscat, the length of daylight hours per day varies moderately over a year, with 10:41 hours of daylight on the 21st of December and 13:35 hours on the 21st of June (Weatherspark, 2020). Cloudiness describes the percentage of cloud coverage of the sky when viewed from a specific location. Muscat experiences two significantly different periods of cloudiness. For nine months, from September through May, the sky is clear for 70% of the day and overcast for only 15% of the time, while for three months, in June, July, and August, the sky is either clear or overcast or in an in-between state during 30% of the time for each of these conditions (Weatherspark, 2020). Given these conditions, it seems justified to set the luminance distribution of the sky for the simulation to “CIE clear sky” as defined by the International Commission on Illumination (CIE) and offered in Revit as a default setting (Autodesk Revit Sky Models Settings, 2020). The illuminance in the rooms is then measured in the digital model through grid points that are set 80cm (32 inches) above ground and at a distance of 30cm (12 inches) from each other.

Other Parameters

In addition to the parameters that can be quantified through the above-mentioned simulations, there are other parameters that contribute to the success of a design at this stage of planning that can be qualified through an analogue assessment, e.g., natural ventilation.

Natural Ventilation

Natural ventilation of buildings is an important factor in energy-efficient design because it not only contributes to a healthy air exchange but also enhances thermal comfort through air movement, which enables the user to perceive air temperature as slightly lower than it actually is. A well-ventilated building saves energy because the periods of time in which a building can be cooled by passive mode without technology can be prolonged.

4. RESULTS

The results from the analyses of insolation, solar access as well as illuminance are first viewed separately for each case and then discussed in comparison.

Results for Case One – Windtower Insolation

The insolation on the opaque as well as the glazed facades is analyzed by dividing the building into four quadrants in accordance with the floor plans that have four separate units per floor. For each quadrant, two building elements are measured, and the results are compared: one is the opaque, outer facade facing the open spaces in front or behind the building, and the other is the glazed, inner facade that is oriented towards the central void space. As can be seen in each series of simulations for the four quadrants for each of the three dates (figures 6, 7, 8, 9), the difference between the insolation on the opaque facade as compared to the one on the glazed facade is significant. While throughout the year, the opaque facades receive between 1,700 Wh/m^2 and 4,000 Wh/m^2, the glazed facades receive between 350 Wh/m^2 and 700 Wh/m^2. In summary, through the Windtower’s design approach, the accumulated insolation on the glazed facades can be reduced by around 80% as compared to the opaque facades, which are exposed to direct sunlight. This is a significant difference and an important precondition for an energy-efficient building.

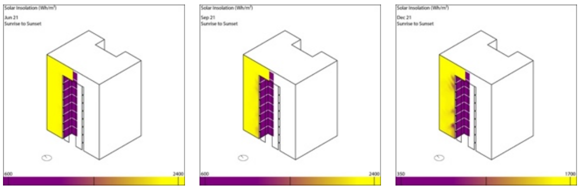

Figure 6. Simulation of insolation (in Wh/m^2) on opaque as well as glazed facades of northwest quadrant for the duration of one day on 21 Jun, 21 Sep, 21 Dec.

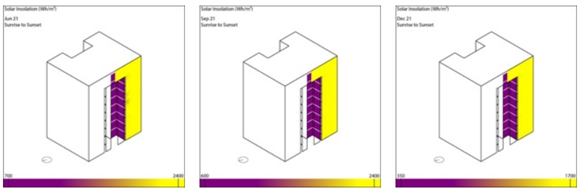

Figure 7. Simulation of insolation (in Wh/m^2) on opaque as well as glazed facades of south-west quadrant for the duration of one day on 21 Jun, 21 Sep, 21 Dec.

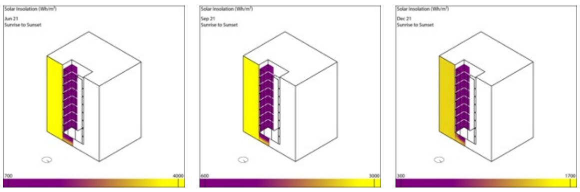

Figure 8. Simulation of insolation (in Wh/m^2) on opaque as well as glazed facades of south-east quadrant for the duration of one day on 21 Jun, 21 Sep, 21 Dec.

Solar Access

The simulation shows that on the typical floor plan of the Windtower, the solar access never rises above two hours per day at any time of the year. The areas where this period of direct sunlight exposure is experienced are very small in comparison to the vast majority of the area where there is none at all (Figure 10). This result proves the effectiveness of the design approach that is based on a simple floor plan with four similar units oriented to different directions but which are differentiated through only one simple, robust and permanently-installed architectural element - a wall on the terrace - that serves as a "sun-blocker". This one wall is fine-tuned for each of the four directions by adjusting its length and position on the terrace.

Illuminance

The simulations of the illuminance levels on a typical floor plan of the Windtower in the morning (9:00 a.m.) and afternoon (3:00 p.m.) on each of the three selected days, show that the illuminance levels are rarely below 50lx nor above 1000lx (Figs 11, 12, 13). There are some minor exceptions; for example, during the morning hours in the southeast apartment, some areas close to the window show illuminance levels higher than 1000lx (Figs. 11, 12, 13). During the afternoon hours in the northeast apartment, some areas have illuminance levels lower than 50lx (Figs 11, 12, 13). However, these are temporary situations that only affect small areas of the overall floor plan. Overall, it can be seen that the illuminance levels within the apartments are generally in a range that provides visual comfort for users. Furthermore, it is remarkable that the outdoor areas of each apartment show only slightly higher illuminance levels than the indoors, which makes them comfortable areas into which the living spaces can be extended. It also means that views from inside to outside have little contrast and thus glare is avoided, which again raises the visual comfort for users.

Results for Case Two – Umbrellahouse

Insolation

The simulation of the insolation on the outer, opaque facades and on the inner, glazed facades of the Umbrellahouse shows that for one day of each of the three days that are representative for the seasons, there is always a stark contrast between the insolation on the two different facades (Figure 14). While the cumulative daily insolation on the inward-facing facades of the glazed courtyards is between 350-700 Wh/m^2, it is mostly in the range of 3-4,500 Wh/m^2 on the fully closed outward-facing facades - in this case, the south and east facades; a difference of around 85-90%. Some minor areas of the glazed facades show slightly higher insolation due to temporary exposure to direct sunlight, but this is deemed rather negligible due to the limitation of the area and the period of exposure. This can be seen in the round courtyard facade in winter and also the south-facing long facades of the rectangular courtyards in spring and autumn as well as its shorter ends in summer (Figure 14). Further exceptions on the outer facade are in summer when the south-facing facade receives less energy due to the seasonally high altitude of the sun, as well as in winter when the east (and respectively the west) facade receives less energy due to the higher degree of the azimuth of the sun.

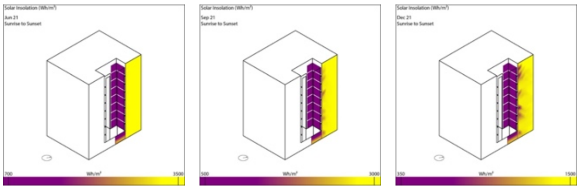

Figure 9. Simulation of insolation (in Wh/m^2) on opaque as well as glazed facades of northeast quadrant for the duration of one day on 21 Jun, 21 Sep, 21 Dec

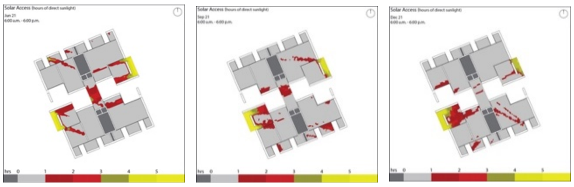

Figure 10. Simulation of solar access on typical floor plan between 6 am and 6 pm on 21 Jun, 21 Sep, 21 Dec

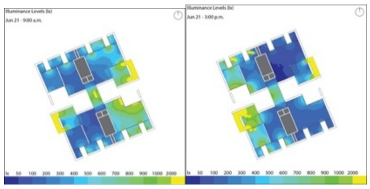

Figure 11. Simulation of illuminance levels (lx) of the typical floor plan on 21 Jun 9 am (left), 3 pm (right)

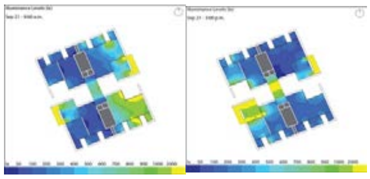

Figure 12. Simulation of illuminance levels (lx) of the typical floor plan on 21 Sep 9 am (left), 3 pm (right)

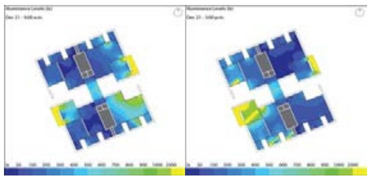

Figure 13. Simulation of illuminance levels (lx) of the typical floor plan on 21 Dec 9 am (left), 3 pm (right)

To complete the assessment of the consequences of the Umbrellahouse's design concept that aims at providing comfortable living spaces with minimal insolation, not only the accumulated insolation on the large glazed facades that envelope the interior living spaces were simulated but also the insolation on the exterior living spaces in the garden. The results show how the elevated volume of the villa shields off solar radiation from the ground floor and reduces the accumulated insolation significantly for around half the area, and in many of these areas up to 95% (Figure 15).

Solar Access

The simulation of the solar access parameter shows that no area of the rooms on the main floor of the Umbrellahouse receives more than 2 hours of direct sunlight at any time of the year, while most of the area received none at all (Figure 16). The least solar access is in summer, while the most are in winter. However, this situation needs to be seen in combination with the overall weather during this period when the outdoor temperatures are pleasant, and potential heat gains can be compensated by natural ventilation.

Illuminance

The illuminance levels for the rooms of the Umbrellahouse are simulated for a typical floor plan, which in this case is the elevated first floor at the three set days of the year at 9:00 a.m. as well as at 3:00 p.m. (Figs 17, 18, 19). What can be seen from these simulations is that the illuminance levels of the rooms on the first floor of the house are always between a minimum of 50lx and a maximum of 1000lx. In the bedrooms, there are some minor incidents of illuminance levels of 2000lx or above; in the morning hours of spring and fall and very scarcely in the afternoon hours of summer as well as in the afternoon hours of winter. These exceptions are too small in area and duration as to matter for the overall assessment of the situation. The large room that wraps around the circular courtyard and contains living, dining, playing, and kitchen zones receives a remarkably even illuminance throughout the year. Only in winter does the south-facing zone receive direct sunlight and show illuminance levels above 2000lx. As mentioned in the discussion of the cases above, such a situation at this time of the year is not ideal but occurs only for a short period of time.

5. DISCUSSION

The results of the simulations of the two case studies can be discussed on two levels. First, what they mean for the research questions of this paper. And second, what do they mean for an outlook onto the bigger picture of the architecture of energy-efficient buildings in Oman as well as in emerging cities in hot climates at large?

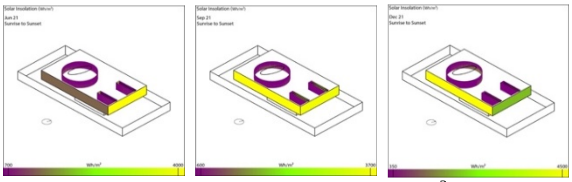

Figure 14. Simulation of insolation (in Wh/m^2) on opaque as well as glazed facades of northwest quadrant for the duration of one day on 21 Jun, 21 Sep, 21 Dec.

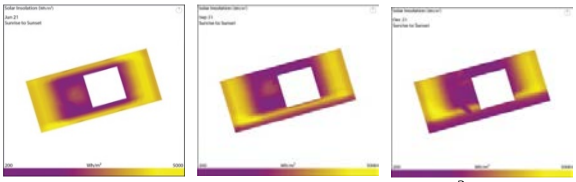

Figure 15. Simulation of insolation (in Wh/m^2) on ground level (garden) for the duration of one day on 21 Jun, 21 Sep, 21 Dec.

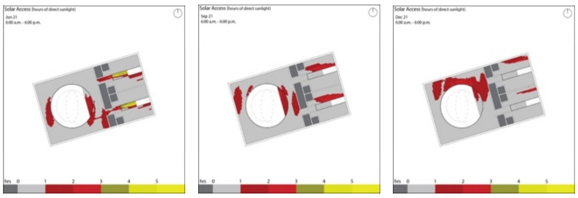

Figure 16. Simulation of solar access on typical floor plan between 6 am and 6 pm on 21 Jun, 21 Sep, 21 Dec.

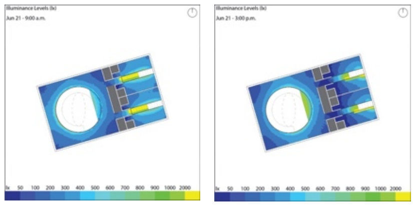

Figure 17. Simulation of illuminance levels (Lx) of the typical floor plan on 21 Jun 9 am (left), 3 pm (right).

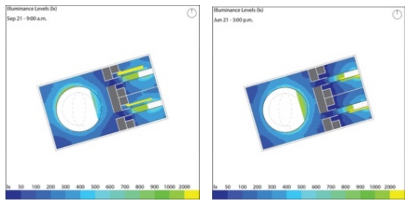

Figure 18. Simulation of illuminance levels (Lx) of a typical floor plan on 21 Sep 9 am (left), 3 pm (right).

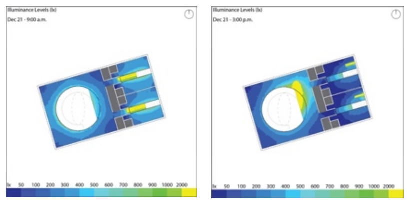

Figure 19. Simulation of illuminance levels (Lx) of a typical floor plan on 21 Dec 9 am (left), 3 pm (right).

Reflections on the Research Questions

On the first research question: The designs of the Windtower, as well as the Umbrellahouse and their successful performance, is proven through the simulations presented in this paper. It reaffirms that the consistent avoidance of heat gains through architectural elements leads to specific idioms of architecture in a hot climate zone: a) the outer envelope becomes radically closed; b) to compensate for this, the building volume needs to incorporate void spaces; c) the openings then orient towards to these inner voids. Such climate-responsive idioms are found in the vernacular architecture of the region but are so far rarely applied in contemporary buildings and urban typologies, at least not in Oman.

On the second research question: The designs show that a focused pursuit of visual comfort requirements leads to a re-balancing of open and closed facades that is different from the vernacular approach. While in the traditional architecture of hot climates, e.g., in Oman, windows are deliberately kept very small and embedded in the plane of largely closed facades, the contemporary designs presented in this paper have very large glass facades. However, these facades are always protected from direct sunlight. The difference between these two approaches is that the former creates visual discomfort due to the stark contrast between the large, dark wall surfaces and the small, very bright light spots from the windows, while the latter provides a comfortable and ample distribution of diffuse and indirect daylight deep into the rooms. Further, the designs demonstrate the advantages of providing two sources of daylight from different directions. In the process of designing these projects, it also became apparent that in hot climates with predominantly clear skies, the provision of daylight needs to be approached with a maximum rather than a minimum illuminance level.

On the third research question: The two designs show that effective cross-ventilation can only be provided if the room configurations are such that corridors are avoided, and rooms have multiple openings, if possible, in different directions. Such an inner logic of space arrangements leads to an outer form that is not compact but spread out or folded. This logic is counterintuitive to the often-formulated aim of keeping the surface-to-volume ratio at a minimum in order to save the facade area and reduce exposure to the hot environment. However, compact volumes tend to become quite deep and thus create insufficiently lit and unventilated interiors. Therefore, designs should avoid compact forms that appear energy-efficient only at first sight and instead prioritize more expansive forms that provide passive cooling through ventilation and visual comfort through evenly distributed indirect daylight.

At this point, it should be added that while the designs have addressed the articulation of the floor plans and facades to adapt to the climatic conditions, they have not addressed the design of the roof yet. The reason for this is that - given the effective application of photovoltaic panels in the region – it is assumed that all buildings should be equipped with a flat roof-top array of the largest possible size to generate electricity and operate as a double roof (Knebel, N & Wassmer, M., 2019).

The findings presented here are drawn from only two case studies, but the conclusions could be transferred beyond these individual cases and could become strategies for designing energy-efficient and comfortable buildings in hot climates. A starting point for further exploration would begin with employing architectural means before adding mechanical solutions.

Other disciplines that contribute to the same goals may pick up the planning process from here but not jump over these fundamental issues. Architecture that consistently translates local climatic conditions into built form does create a local idiom and thus an identity for a place - a quality that should be conceptualized from real requirements rather than be construed from an artificial image as is so often the case (Knebel, 2019).

6. CONCLUSION

While this paper makes a case for architectural design to be emphasized in the quest for energy-efficient buildings, the results have consequences for urban design, too. The paper shows that when considering the climate-adaptiveness of buildings in a hot climate like in Oman, quite unusual forms evolve. For example, the Windtower is a bulky volume with closed exterior facades and inward-looking apartments towards a central void space. Which typology would this be in the known terms of urban design? Or, the Umbrellahouse is a flat volume with closed exterior facades, and inward-oriented rooms elevated over a garden. As which typology would this be categorized in urban design? In an attempt to describe these typologies for the two cases, one could say that the Windtower is a ‘flipped block’, in which the courtyard moves from a horizontal to a vertical position. Similarly, the typology of the Umbrellahouse could be seen as a ‘flipped slab’, in which the thin flat volume is no longer in a vertical but in a horizontally elevated position (Figure 20).

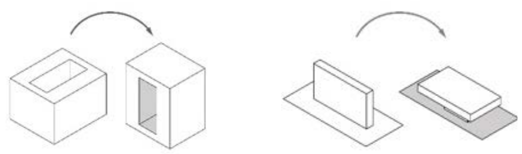

Figure 20. Transformation of existing typologies as a consequence of climate adaption.

Seen from this perspective, the results from this paper open up a necessary and more general discussion about appropriate building typologies for this region and climate. These two potentially new typologies are certainly not the only ones that are appropriate for the context of residential buildings in the hot climate of Oman. Instead, they are only the beginning of a necessary search for appropriate and innovative typologies. Finally, the fact that major large-scale urban design projects in Oman (such as Madinat Al Irfan, the new downtown of Muscat, or Al Duqm, the new harbour city on the Arabian sea) neglect specific climate implications and instead propose urban typologies that originate from the temperate climate zone and are not necessarily appropriate for a location within the hot and arid climate zone, show the urgency for this discussion to be carried on.

It can be summarized that for climate-adaptiveness on both scales, architectural and urban, the first step is to exploit the potential of form with a self-imposed limitation to pursue simplicity before moving on into the potentially much more complex realms of material sciences and systems automation. This paper shows that the rule of thumb for designing for energy efficiency and comfort in hot climates through negotiating illuminance, ventilation, and insolation can be subsumed as an inversion of the modernist architect’s credo and says: “Light, Air, and no Sun”.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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