A reinterpretation of vernacular strategies for building envelopes in hot and arid climates: guidelines for façade design

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Abstract

In the context of various scenarios of global climate change and the imminent threats posed by escalating global temperatures, architects and urban planners must reflect on the lessons to be learned from the established model of vernacular architecture in arid climates. When closely examined and comprehended accurately, vernacular architecture offers a repository of readily applicable strategies that can be expanded upon and implemented in contemporary construction. This paper focuses on the benefits derived from incorporating height-to-width ratio (H/W) in urban settings, window-to-wall ratios and shading mechanisms inferred from vernacular architecture into envelope design for contemporary residential development. It employs the hot-arid climate of Cairo City, Egypt, as a reference context for this research proposed study. The paper elaborates on the methodologies and processes utilized to transform principles of vernacular strategies into quantifiable benchmark. This is accomplished through the integration of environmental performance simulations, including thermal and daylight conditions, which informed the exploration of potential architectural solutions. The outcome is a characterization of design elements inherent in vernacular architecture, leading to design recommendations for contemporary residential buildings in hot and arid climates, with emphasis on window-to-wall ratios and shading mechanisms.

Keywords - . Vernacular Architecture, Hot-arid climate, Adaptation, Passive strategies, Parametric Guidelines.

1. Introduction

1.1 Dry hot Climates: current distribution, future projections, and impact on global population

Climate exerts a great influence on both the choice of construction materials within a region and the design of buildings that provide essential shelter. Consequently, establishing a climatic framework is essential to understand the origins of vernacular architecture, its adaptations to challenging local conditions, and its potential applications in an era of climate change. This study specifically focuses on hot-arid climates following the Köppen-Geiger climate classification system. According to this classification, arid (B) climate zones dominate our planet, covering approximately 26% of its land area and extending roughly between 35° and 35° North and South of the equator [1]. Over recent decades, these arid climate zones have expanded at the expense of temperate and middle-latitude boreal climates, a trend predicted to persist throughout the 21st century [2]. To truly grasp the ramifications of climate change on urbanization and human well-being, it is essential to cross-reference current and projected climate scenarios with global population projections. As global temperatures are anticipated to rise by 1.5°C, 2°C, and 3°C, the severity of hot-dry climates is expected to intensify, particularly in regions such as southern Mediterranean Europe, Central and West Africa, Central America, the Amazon, and the west coast of South America. Consequently, due to 1.5°C, 2°C, and 3°C warming, the exposure of the population to hotter and drier climates is projected to increase by 93 million, 201 million, and 359 million, respectively [3].

1.2 Dry hot Climates: climatic conditions & vernacular passive strategies

Climate plays a pivotal role in shaping architectural design, with variables such as temperature, solar radiation, precipitation, and humidity being key determinants [4]. Regions within this climate are characterized by prolonged summers and brief winters, with daytime temperatures frequently surpassing 40 degrees Celsius and nighttime lows dipping below 25 degrees Celsius. Adding to these conditions, the average annual global radiation on a horizontal surface surpasses that of other climate zones, averaging approximately 1700-2000 kWh/m2 per year. Throughout the summer, sky illuminance levels soar from 75,000 lux to 10,500 lux, far exceeding the optimal indoor daylighting range of 300 to 2000 lx. In summary, arid climates present significant challenges, with excessive indoor lighting levels and occupants' discomfort stemming from intense solar heat gains being the foremost concerns. For arid climate regions grappling with escalating global temperatures and climate change, longstanding vernacular architecture stands as a pivotal model.

Density has an important impact on how much sunlight is absorbed, reflected, and stored in the fabric of a city, both in terms of incoming short-wave radiation and outgoing long-wave radiation. Common to cities in hot, dry climates is a combination of two main urban planning principles: the aspect ratio of the canyon, which is defined by factors such as its height-to-width ratio (H/W) and the building orientation. While it may have minimal impact on heat loss, precise orientation becomes crucial for harnessing optimal solar gains [5]. It is advisable to align buildings along the East-West axes to mitigate excessive solar heat accumulation and to facilitate shading of facades that are prone to direct sunlight, such as those facing East and West. Ideally, a slight eastward deviation from true south, typically around 15° east, proves to be more efficient, as it minimizes solar heat absorption on the western facade during the summer months [6]. To effectively manage sunlight absorption, it is imperative to reduce the number of windows in all directions and maintain a low window-to-wall ratio [7]. Additionally, incorporating external shading devices during the summer months is vital. These devices effectively obstruct excessive solar radiation from infiltrating building interiors while still permitting solar radiation to enter during the winter [8].

The materials, technologies, and architectural forms associated with vernacular architecture have long been acknowledged for their suitability to local climate conditions and their capacity to serve as a foundation for environmentally conscious design. It has long been understood that architectural needs within this climate zone typically revolve around offering shade and ensuring thermal comfort regardless of outdoor temperature fluctuations [1]. However, research projects that numerically demonstrate the benefits of embedding the described strategies within building envelopes are rare. Expanding on the classification of passive strategies by their response to one or more direct environmental stimuli [9],. this study attempts to convert the abstract definition of vernacular architecture features into measurable criteria.

2. Method

The study was conducted through a four-step research and methodology framework, with the first step dedicated to literature review, while the subsequent three steps centred on analytical exploration. Extensive research and literature review focused on raising knowledge on the benefits of vernacular architecture in hot, dry climates by using key phrases like Vernacular Architecture, Local Building Techniques, Arid Region Architecture, Climateresponsive Solutions, Traditional Building Methods, and Thermal Comfort (1). The next step (2) involved analyzing and reviewing the identified publications, categorizing passive strategies and architectural features based on their impacts on comfort and identifying those particularly relevant in the design of building envelopes, being: height to width ratio (H/W) of urban settings, window to wall Ratio (WWR) and shading devices.

Step (3) involved the establishment of an Analytical Base Case to facilitate comprehensive numerical investigations. Climate data from the Cairo International Airport weather station through EnergyPlus Weather files (.EPW) are available on the Ladybug tools website. Initially, a range of urban design configurations was set up, each consisting of a grid of residential blocks with diverse orientations and variable H/W (height-to-width) ratios. The different configurations were tested against their effect on the minimisation of cumulative solar radiation levels on vertical facades kWh/m2 and classified from optimal to less optimal. One, among the optimal scenarios, was selected as a base case to illustrate the steps for the subsequent phase of analytical work.

To perform essential indoor condition testing, the study selected one of the optimized urban configurations and carried out an analysis focusing on the annual cumulative solar radiation expressed in kWh/m2 on facades oriented in different directions. This approach was integral to investigating the impact of vernacular Window-toWall Ratios (WWR) on multi-story residential buildings as a passive design strategy. The assessment of WWR, rooted in vernacular architectural principles, was aligned with contemporary performance metrics, including Daylight Autonomy (DA) and Daylight Factor (DF). These metrics were subsequently calibrated to adhere to modern indoor lighting standards, and this iterative process yielded a comprehensive set of recommendations and design guidelines for optimizing WWR. Building upon the conclusions and guidelines derived from the Window-to-Wall ratios, traditional components of daylighting systems were subjected to a comprehensive evaluation and enhancement. This involved an examination of the type, orientation, and dimensions of vernacular shading devices, with the primary objective being to meet the minimum illuminance standards stipulated in the Egyptian Building Energy Efficiency Code (BEEC) [10]. To assess the daylighting requirements for units across all orientations and floors in the Base Case Study, point-in-time illuminance levels were tested over December 21st (a typical winter day) and June 21st (a typical summer day) at 9 AM, 12 PM, and 3 PM. These illuminance simulations played a pivotal role in identifying the specific daylighting needs. Furthermore, these simulations were juxtaposed with indoor thermal simulations to establish a correlation between window-to-wall ratios, illuminance conditions and the thermal performance of the units.

Step (4) consisted of consolidating this holistic strategy encompassing vernacular passive techniques into a comprehensive set of guidelines. These guidelines encompassed recommendations for building heights relative to street width, window-to-wall ratios, and shading devices for envelope design. The visual depiction of the methodological approach can be observed in Figure 1.

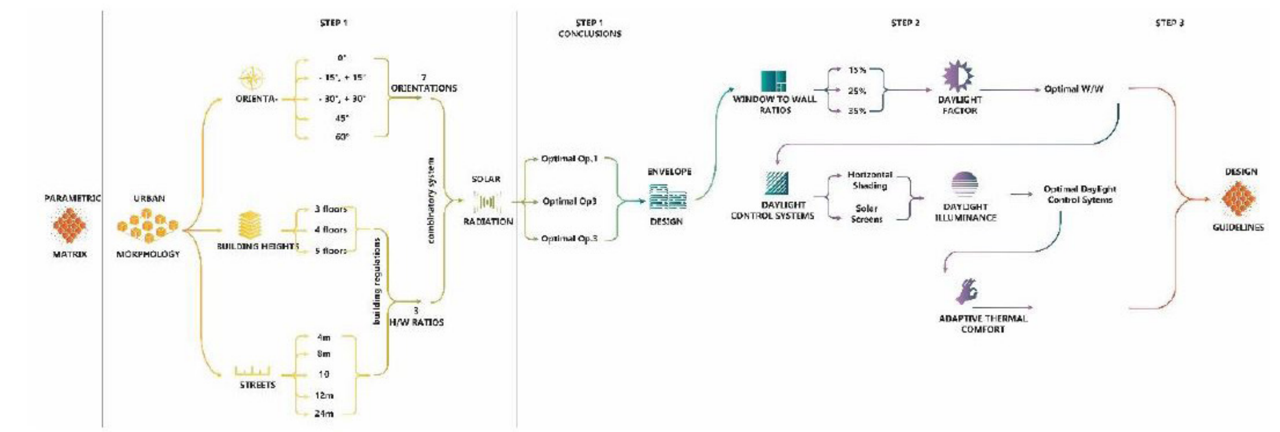

Figure 1: Research and methodology approach for the analytical work conducted on the Base Case Study.

2.1 Analytical Base Case: Urban Morphology

When comparing deep traditional urban canyons (H/W approximately 2.2) with modern urban canyons (H/W ratio approximately 0.46), it is evident that the second is related to urban surfaces' higher exposure to solar radiation and as a consequence of higher air temperature in [11]. The position of the sun must be considered when planning any building or cluster of buildings on-site, especially in the warmer months. In hot climates, the sun is the major source of heat; despite having little impact on heat loss, orientation is essential for receiving good solar gains [5]. The matrix of urban configurations presented in this study encompassed H/W ratios spanning from 1.6 (representative of traditional dense city layouts in hot, arid climates) to 1.25 (an intermediate ratio), down to 0.8 (reflecting shallow urban canyons more commonly found in contemporary urban development). These H/W ratios were systematically combined with different orientations, including 0°, 15°, 15°, 30°, -30°, and 45° from the north-south axis.

Subsequently, these combinations of H/W ratios and orientations underwent rigorous testing and classification using a multi-objective optimization approach focused on minimizing cumulative solar radiation in kWh/m2 (expressed as comparative solar factor) on building facades, particularly on the south and west orientation, so to reduce heat gains over the summer periods. This paved the way for formulating urban design recommendations to guide new developments, serving as the foundation for the subsequent phase of analytical work. One of the optimised urban configurations obtained by this process served as the foundation for our investigation into facade conditions, specifically focusing on aspects such as the Window-to-Wall ratio and the incorporation of shading devices. This configuration utilized a grid with a 25m x 25m footprint and urban blocks that reached a height of 13 meters, consisting of a 4-meter-high ground floor and additional 3-meter-high residential floors, maintaining a building height-to-street width ratio of 1.25 and an Orientation of 0 degrees to North South, as illustrated in Figure 2. These urban configurations served as the foundation for our investigation into facade conditions, specifically focusing on aspects such as the Window-to-Wall ratio and the incorporation of shading devices.

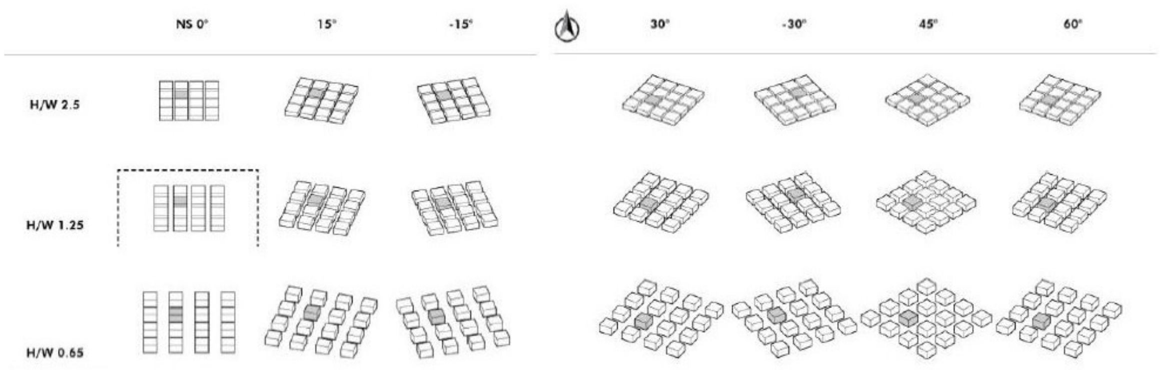

Figure 2: Visualizing tested orientations and H/W Ratios: Analytical Combinatory matrix for various urban configurations (Optimised Base Case Highlighted).

2.2 Analytical Base Case: Window-to-Wall ratio

In hot arid regions, the challenge lies in effectively integrating the primary functions of windows: good lighting, ventilation, and view. This often necessitates addressing each function separately due to their conflicting requirements. By conducting thorough literature reviews, the authors have discerned pertinent design principles imparted by vernacular architecture in hot-dry climates. Size: Instead of a few large openings, a series of small apertures is typically employed. This approach ensures privacy, security, uniform ventilation, and protection from direct sunlight. Overly large openings, while providing ample light and views, disrupt wind circulation and increase the risk of glare [12]. WWR: In arid climates, optimal sunlight control calls for low window-to-wall ratios. For various orientations, recommended ratios include approximately 0.16 for South-West facades, 0.09 for North-West facades, 0.18 for North-East facades, and 0.07 for South-East facades [13]. The literature review findings were quantified and implemented in the analytical Base Case for numerical assessment and testing of the WWR's impact in multi-story residential buildings. The WWR analysis spanned two steps.

The first step consisted of evaluating the daylight performance of WWR aligned with vernacular architecture (15%) against Daylight Factor (DF) and Daylight Autonomy (DA) benchmarks. The climate analysis of Cairo unveiled that, on average, the sky is covered 38% of the time. Consequently, the Daylight Factor (DF) was adopted as a dependable daylight metric, aligning with DGNB standards. According to these standards, when more than 50% of the usable area within a building achieves a DF > 3, it is considered "good"; > 2 is categorized as "medium"; > 1 falls under "slight"; and < 1 is labelled as "none." Furthermore, an illuminance threshold of 300 lux was utilized as the reference value for the Daylight Autonomy (DA) metric [14]. The second step revolved around the optimization of the WWR. Iterations with increased WWR (ranging from 25% to 35%) were conducted for daylighting optimization. Surface treatments and colours influencing daylight assumed external and internal wall reflectance of 30% and floor and ceiling reflectance of 30%.

2.3 Analytical Base Case: Systems for Daylight Control

The arid desert climate offers excellent opportunities for maximizing the use of natural light to illuminate indoor spaces in buildings during the daytime. However, the intense sunlight prevalent in desert regions like Egypt poses challenges. It leads to direct solar radiation entering indoor spaces, causing unwanted glare and resulting in discomfort, particularly during the summer months. A traditional solution employed to address this issue is the "Mashrabiya," a type of vernacular shading system. The Mashrabiya consists of cantilevered balconies enclosed with wooden lattices made of interconnected cylindrical elements held together by spherical joints [14]. Mashrabiyas come in various shapes and sizes with no fixed dimensions. However, the literature review has indicated that these structures typically extend about 60 cm into the street. Furthermore, considering the thickness of the exterior wall and the projection of the Mashrabiya, the width can range from 1.0 to 1.2 meters [15]. To achieve a geometric simplification and parameterization of its fundamental elements, the authors have classified the components of the Mashrabiya into the following two categories: horizontal cantilever ranging from 60 cm to 90 cm in length and solar screens with a degree of 50% 75%and 90% perforation, as seen in Figure 3.

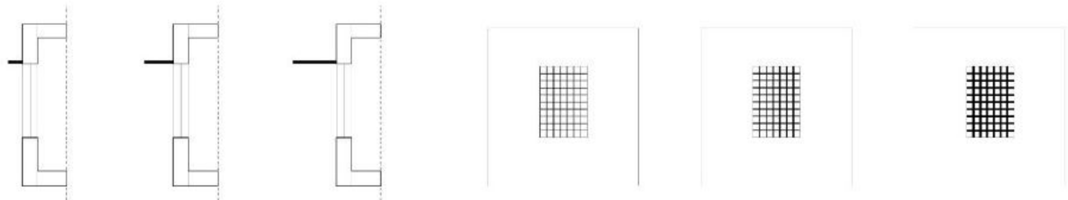

Figure 3: Visual Representation of Horizontal Shading Devices at 30cm, 60cm, and 90cm Projections (Left to Right) and Solar Screens with Opening Ratios: 50%, 75%, and 90% (Left to Right).

3. Results and Discussion

3.1 Urban Morphology

In the context of Cairo, it was concluded that, in accordance with what was found through the literature review, the urban canyon ratio (H/W) of urban fabric seems to have a bigger impact in reducing the total cumulative solar radiation on building facades compared to orientation in urban configurations. In this climatic context, the impinging solar radiation on faces (expressed in the comparative number of solar factors) is suggested as a reliable numerical indicator for defining urban development guidelines inferred from the vernacular. For urban configurations with comparable urban canyon (H/W) ratios, the Total Solar Factor did not change with the urban grid orientation changes. Deep vernacular urban canyon (H/W 2.5) has a recurring Total Solar Factor on building facades of TSF= 1 (compared to the base case). Intermediate urban canyons (H/W 1.25) resulted in a recurring Total Solar Factor on building facades of TSF= >1.6 - 1.7< when compared to the TSF =1 for the deep urban canyon, inferred from the vernacular. Shallow-contemporary urban canyons (H/W 0.60) resulted in a recurring Total Solar Factor on building facades of TSF= 2.2 when compared to vernacular urban canyons. Urban grid orientation can be used effectively to minimise impinging solar radiation on the South and West facades so as to reduce heat gains over the summer period. This led to the definition of optimised urban configurations and design recommendations for new developments summarised this way: H/W 0.65, Orientation 0° - H/W 1.25, Orientation 0° - H/W 2.5, Orientation -30°

3.2 Window-to-Wall ratio

Solar radiation analysis for the four differently oriented facades in the second optimised scenario (Orientation 0° - H/W 1.25, Orientation) was carried out to understand the vertical distributions of the cumulative solar radiation. South and East facades receive a comparable amount of direct solar radiation spanning from an average of 1000 kWh/m2 on the top third floor down to an average of 400 kWh/m2 on the bottom floor. The floors on the West went from av. 640 kWh/m2 (3rd F) to 300 kWh/m2 (GF), while the floors on the North went from av. 260 kWh/m2 (3rd F) to below 100 kWh/m2 (GF). Daylight Autonomy and Daylight Factor were tested for 10.0m wide and 7.5 m deep rectangular flats. When applying the WWR set at 15%, several notable patterns emerge, as illustrated in Figure 4. Ground floor apartments, regardless of orientation, exhibit a slight Daylight Factor exceeding 1%, while on the third floor, all four oriented apartments achieve a medium Daylight Factor surpassing 2%. In terms of Daylight Autonomy, the ground-floor apartments fall below the 50% threshold, reflecting limited autonomy. Similarly, the North and West-oriented apartments on the third floor also manifest a Daylight Autonomy below 50%. Therefore, the analysis unveils that the inferred WWR of 15% (drawn from vernacular architecture) fails to meet the standards.

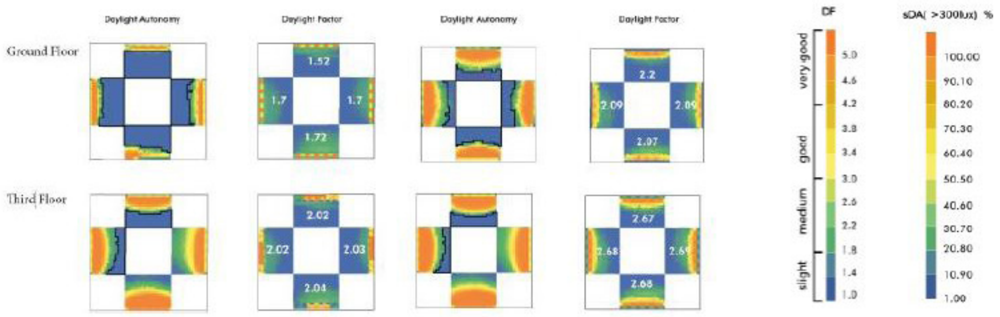

Figure 4: Daylight Autonomy and Daylight Factor analysis for ground floor and top floor apartments, WWR 15% (on the left) WWR .25% (on the right).

However, upon transitioning to a WWR of 25%, improvements become evident. On the ground floor, all four oriented apartments achieve a medium Daylight Factor exceeding 2%, a trend that continues on the third floor. Moreover, Daylight Autonomy experiences a positive shift, with ground-floor apartments achieving or exceeding the 50% threshold, indicating enhanced autonomy. Notably, three apartments on the third floor also achieve a Daylight Autonomy of 50% or higher, further underlining the benefits of the increased WWR. By adjusting the WWR to 35%, the medium illuminance standards are satisfied at the ground-floor level. Intermediate levels with a WWR ranging between 25% and 35% are deemed to meet the minimum illuminance standards adequately. The outcomes of the analytical work culminate in recommendations regarding the WWR, illustrated in Figure 5.

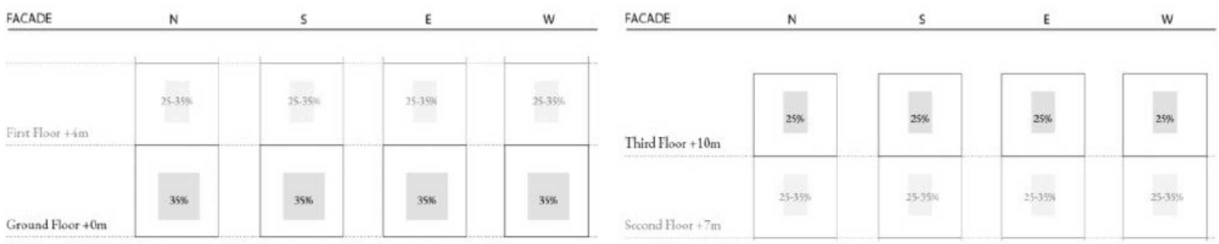

Figure 5: WWR guidelines for North, South, East and West oriented apartments.

3.3 Systems for Daylight Control

Testing was conducted on a standard summer day, revealing notable disparities in daylight levels between ground-floor and third-floor apartments in both the Base Case Study and the configuration adhering to the Window-to-Wall Ratio (WWR) guideline. These variations had the potential to cause discomfort for occupants. They correlated the average daily temperatures during these time intervals with the instances of pronounced daylight contrast. This is illustrated through graphs in Figure 6. The outcomes of the comparative analysis underscore the remarkable efficiency of horizontal shading elements in controlling high-altitude sunlight during the summer season, leading to a noteworthy average reduction of approximately 2.5 degrees Celsius in indoor operative temperatures within the apartments. The indoor operative temperatures of the North, West, and South apartments on the ground floor remain comfortably within the desired range. Meanwhile, the East apartment's operative temperature approaches the lower limit of the comfort band. This is illustrated in Figure 7.

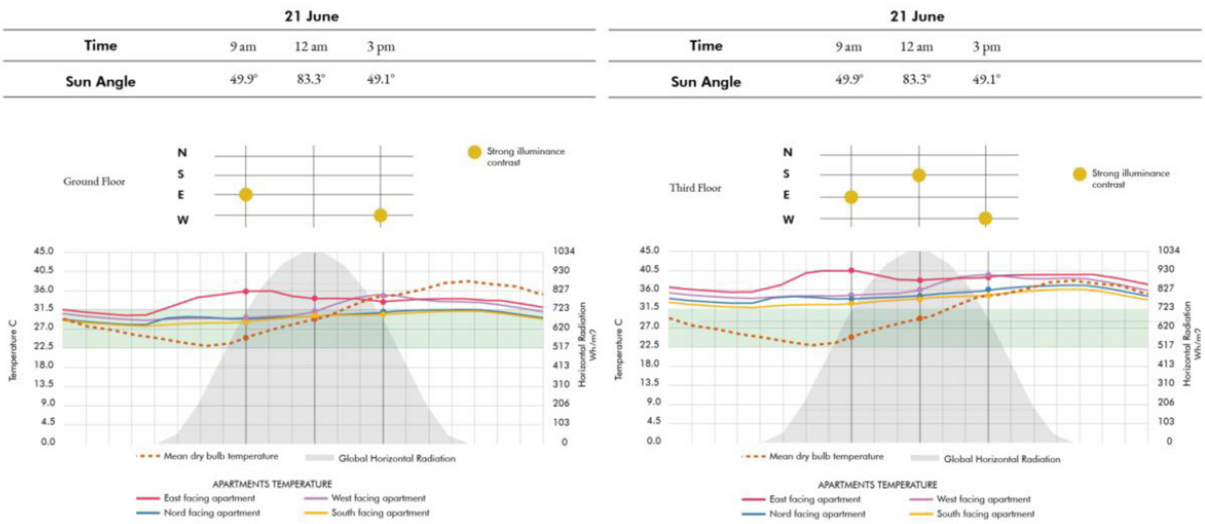

Figure 6: Comparing Excessive Daylight Conditions and Indoor Temperatures on a Typical Summer Day (June 21st) for Four Oriented Apartments in the Base Case Study, including Ground Floor and Top Floor Scenarios.

Using the same analytical approach, the authors extended their investigation to a typical winter day (December 21st) to assess the performance of solar screens. Their findings revealed that during the winter season, it's advisable to maximize the admission of solar radiation to harness heat gains, and effectively utilizing solar screen systems can aid in daylight distribution and mitigating excessive contrasts [14]. Additionally, findings indicate that solar screens can raise the indoor operative temperatures of the apartments by an average increase of around 1 degree Celsius and that solar screens lead to notably reduced fluctuations in operative temperatures across all apartments, both on the ground floor and the third floor. The outcomes of the analytical work culminate in recommendations regarding the application of WWR, horizontal shading devices and solar screen, as illustrated in Figure 8.

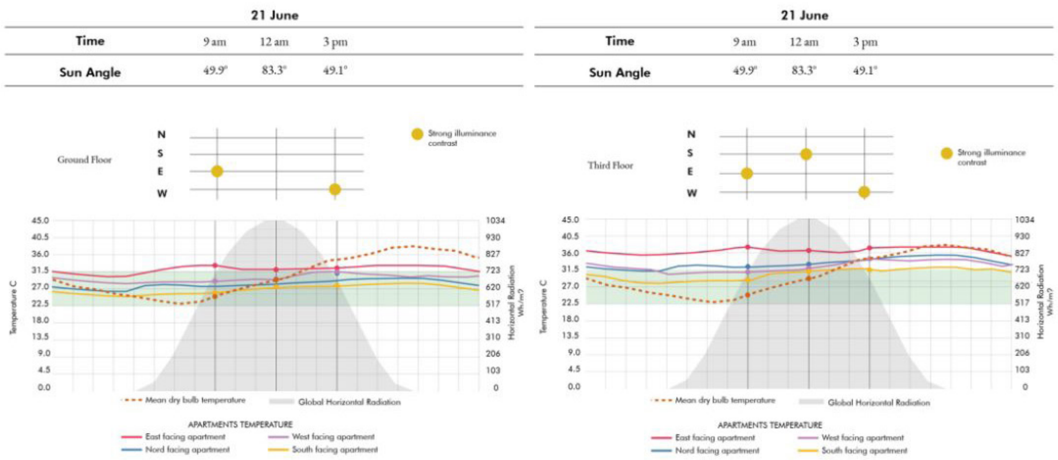

Figure 7: Comparing Indoor Temperatures on a Typical Summer Day (June 21st) for Four Oriented Apartments in the Base Case Study when added horizontal radiation, including Ground Floor and Top Floor Scenarios.

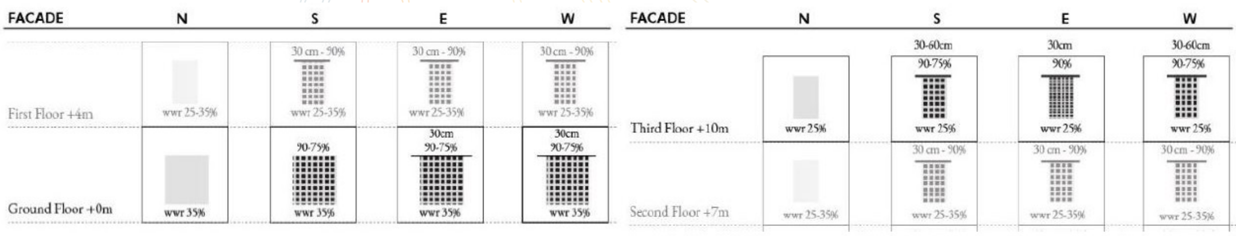

Figure 8: Guidelines for WWR, horizontal shading devices and solar screens for Base Case Study.

4. Discussion

This research aimed to illustrate methodologies and processes utilized to transform principles of vernacular strategies into quantifiable benchmarks by looking at the performance of vernacular urban canyons, window-towall ratios and shading devices on daylight and thermal comfort in hot-dry climates, where Cairo is taken as representative of the climatic conditions. As far as the result and discussions are concerned, deep vernacular urban canyons (H/W 2.5) consistently result in a Total Solar Factor of 1, while intermediate canyons (H/W 1.25) show a factor between 1.6 and 1.7, and shallow-contemporary canyons (H/W 0.60) result in a factor of 2.2, compared to vernacular canyons. Additionally, adjusting the urban grid orientation effectively proved to reduce solar radiation on South and West facades, thus playing a pivotal role in enhancing indoor lighting and thermal comfort within residential structures. As a result, the optimized urban configuration and design recommendations are H/W 0.65 with a 0° orientation, H/W 1.25 with a 0° orientation, and H/W 2.5 with a -30° orientation.

The vernacular architecture standard of 15% WWR revealed Daylight Autonomy (DA) and Daylight Factor (DF) levels insufficient to achieve the contemporary standards of comfort in both ground-floor and third-floor apartments. Transitioning to a 25% WWR significantly improved daylight metrics for both floors and a 35% WWR on the ground floor met minimum illuminance standards. The study's key finding is the recommendation for intermediate WWR levels, specifically between 25% and 35%, as they consistently achieved sufficient illuminance levels, indicating their effectiveness in optimizing daylight performance in residential buildings. Shading devices, encompassing both horizontal shading structures and solar screens, proved to be an efficient strategy for enhancing indoor comfort by effectively managing high levels of indoor illuminance and indoor temperatures. The efficacy of horizontal shading components in regulating high-altitude summer sunlight results in a substantial reduction in indoor operative temperatures, and solar screens emerge as valuable contributors to daylight distribution and heat retention during winter. Certain limitations ought to be considered when interpreting these results. Analytical Base Case, while providing a simplified representation of the average urban set-up and interior unit set-up, may not fully encapsulate the complexity and variability of new residential developments.

5. Conclusion

This study underscores the relevance of harnessing vernacular architectural wisdom to address the challenges presented by contemporary construction in arid climates. The outcomes derived from typical summer and winter days in a hot-dry climate, offer a comprehensive insight into the potential enhancements in thermal comfort achievable through the application of guidelines deduced from the assessment of vernacular urban features, WWR and shading devices. Although most of these recommendations can currently be applied to buildings in similar climate conditions, climate change projections suggest that hot-dry regions are expected to expand considerably in the coming decades. In this sense, lessons and methods from the vernacular are likely to be relevant and applied more extensively. Ultimately, this study offers a foundation for architects and urban planners to draw inspiration from the past and seamlessly integrate vernacular wisdom into the present, ensuring the sustainability and resilience of architecture in arid climates.

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