Chapter 1
Proposing a New Method for Fenestration Shading Design in Prefabricated Modular Buildings

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Abstract Use of prefabricated construction in developing countries has been increased lately; (for several purposes i.e. educational, industrial, recreational, commercial, etc. as well as temporary homes in post-disaster situations) while the minimum consideration regarding energy efficiency and bioclimatic design strategies are paid attention in this regard. Typically, these buildings are constructed based on industrial production systems and are installed through a modular design process. Subsequently, their fenestration design mainly follows the modularity of envelope panels -in size and geometry- and impacts of environmental factors as solar gain, natural ventilation, and heat transmission are neglected in design decisions even though they play an important role in building energy consumption scales. This study aims to analyze windows and their shading systems in a mid-range altitude and temperate-humid climate in Iran. According to the comfort zone suggested by ASHRAE, the time intervals of the year which necessitate shadows on the windows surfaces are determined. On the condition that shading is provided for the interior spaces, comfort condition is guaranteed needless of any auxiliary solutions. On the basis of the attained sun/shadow calendar, the matrix of fenestration design alternatives is studied in Ecotect software. Parameters as windows geometrical ratio, shading type (vertical, horizontal, mixed), and proportional shading size are studied in each geographical directions and the optimized solutions are proposed in order to provide shadows in the required time periods. This architect-friendly method tried to equip designers with non-numerical algorithmic programs and assist them in energy efficient modular fenestration design. The obtained prototypes are utilizable in prefabricated modular buildings meanwhile the decision-making procedure could also be applied in other altitudes and climatic regions to gain similar models.

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1.1 Introduction

A building designer needs to find the best solution to satisfy various requirements in different design aspects. Regarding air-conditioning solutions, designers prefer to adopt mechanical systems to achieve the required indoor thermal comfort, which results in increased energy consumption in buildings. Thus, buildings are responsible for a substantial part of energy consumption, mostly the result of the heating, cooling, and artificial ventilation systems of a building [1]. Thus, more investigations are needed to determine sustainable alternatives and passive techniques to avoid high rates of energy use.

Solar heat gain is identified as one of the main contributors to overheating in residential buildings. Windows, as the transparent parts of the envelope, have a significant role in the amount of heat gain and the thermal performance of the building. The shape, size, thermal properties, orientation, and shading of windows determine the visual and thermal comfort for the occupants inside buildings [2]. The high cost of advanced glazing types makes them inappropriate strategies for low-cost projects such as prefabricated temporary buildings. Therefore, there is a general perception that sustainable solutions are not cost-effective for temporary types of buildings. This attitude has caused considerable negligence toward energy-efficient temporary buildings, although solar heat gain can be simply controlled by introducing optimized shadings to minimize solar transmission and heat gains through glazed areas [3].

On the other hand, the recent development of building simulation tools has been a revolution in the manual calculation of bio-climatic and solar design; this necessitates an up-to-date systematic approach to organize a step-by-step method assisted by the appropriate simulation software.

This chapter explores the methodology linked with the architectural design process to provide modular buildings with shading devices for hot periods without deprived the occupants of pleasant sunshine in the cold season.

Finally, this work aims to suggest the optimized properties of window shading devices to provide internal spaces with maximum thermal comfort. It also provides designers with the adequate knowledge to design shading devices as an integral part of the fenestration system.

1.2 Research Background

Design of shading devices has been reported in the literature from different aspects, such as illuminance level, visual comfort, building energy consumption, solar gain, and natural ventilation. Indeed, several studies have been carried out to demonstrate the significant effects of appropriate shading on the thermal performance of internal spaces. In the early 2000s, the C.E .Faculty [4], Gugliermetti and Bisegna [5], and Tzempelikos and Athienitis [6] all conducted studies to explore the effects of different shading design strategies on thermal performance improvement in indoor environments and provided the best solutions as design guidelines. A number of researchers attempted to form accurate guidelines for the design of shading devices and to provide interior spaces with the best possible thermal comfort [7]. Other studies combined other fenestration parameters with shading device properties to recognize the most effective items for reduction of building energy consumption [8].

There are also studies that focused on a specific shading type, such as fixed/movable, internal/external, and horizontal/vertical louver shadings by taking advantage of the capabilities of simulation tools; in the primary steps, Datta [9] in 2001 used TRNSYS to study many horizontal shading variables in various locations in Italy. Palmero-Marrero and Oliveira [10] conducted a similar study in many different latitudes and showed the great impact of shading devices on saving energy loads. Hammad and Abu-hijleh [11] investigated the energy consumption of external dynamic louvers, integrated to office building facades, in AbuDhabi. In 2014, the performance of internal shading devices was compared with external installations by Atzeri et al. [12] in terms of heating/cooling loads.

More recent literature has reported optimization algorithmic programs to classify shading devices. Some of these take a multi-objective optimization approach including a shading system whereas others specifically consider shading devices. Manzan [13] used a genetic optimization to identify a possible geometry to achieve the lowest energy impact. Chua and Chuo [14] examined a novel approach based on an established value that measures the envelope thermal performance in high-rise residential buildings to determine the most suitable shading devices for different orientations of the building.

Tahbaz [15] introduced a graphical, geometric, and step-like method, using the "shading mask" and "climatic needs calendar" initially developed by Olgyay [16, 17], and applied this approach to an inadequately shaded outdoor space. By this method, shadow in the necessary periods of the pattern year was provided to modify the inappropriate existing sunshade. In a following study by the same researcher [18], a generalized methodology was suggested for the solar design of buildings in preliminary design stages. In the sequential method suggested by this study, six simple steps are followed to achieve the efficient sunshade for any architectural project. The "climatic needs calendar" in solar design studies was also applied in the work of other researchers [19, 20]. Also, Krüger and Dorigo [21] applied the shading mask procedure to run a daylighting analysis with RADIANCE and ECOTECT in a public school for different time schedules and orientations. The aforementioned efforts that applied the "Olgyay" recommended procedure are mostly accomplished regardless of powerful user-friendly non-numerical simulation software that lets architects analyze solar aspects of the project easily and quickly in a visual interface.

1.3 Methodology

1.3.1 Identifying Shadow Need Periods

Human thermal comfort is related to several factors such as air temperature, air movement, amount of clothing worn, and activity level including the human body itself [22]. Uncomfortable thermal conditions affect a person's productivity, health, and quality of life. According to ASHRAE 55 [23], thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." The Givoni bioclimatic chart [24, 25] considers human and climatic measures as well as building envelope effects and, in this chapter, is used as a proper predictor to analyze the climatic needs of interior spaces. Figure 1.1 shows the thermal zones in which providing shadow (blue line) or shadow+ natural ventilation (green line) guarantees indoor thermal comfort. In other words, so long as natural ventilation is considered for internal spaces, through locating appropriate openings in windward and leeward sides, thermal comfort is satisfied for both zones.

On the basis of Givoni's bioclimatic index, equivalent temperature lines within the "climatic need calendar" are drawn. In Fig. 1.2, the "climatic needs calendar" has two perpendicular axes for days and hours, including all periods of a year. It is utilized to distinguish different climatic needs in various time periods: sunshine need, shadow need, shadow + ventilation need, cold conditions, and very hot conditions. Based on the average hourly climatic data (including temperature and relative humidity, which allow us to gain an effective temperature), the equivalent temperature lines are drawn in the software of Surfer 14. Surfer is a powerful mapping program, very practical in various fields of engineering and scientific studies, which creates a grid-based map from an XYZ data file.

This calendar demonstrates time periods at which shadow provision has a significant role in indoor thermal comfort. The "time zone" area enclosed within M curves needs attention regarding shading system design. A shading device must be made such that the glazing surface is protected exclusively in these periods during the year. The periods during sunray penetration must be avoided or be allowed in the interior spaces are determined. Consequently, the sunshade pattern is designed according to periodic shadow needs and, ultimately, shading devices are proposed to balance these two conditions.

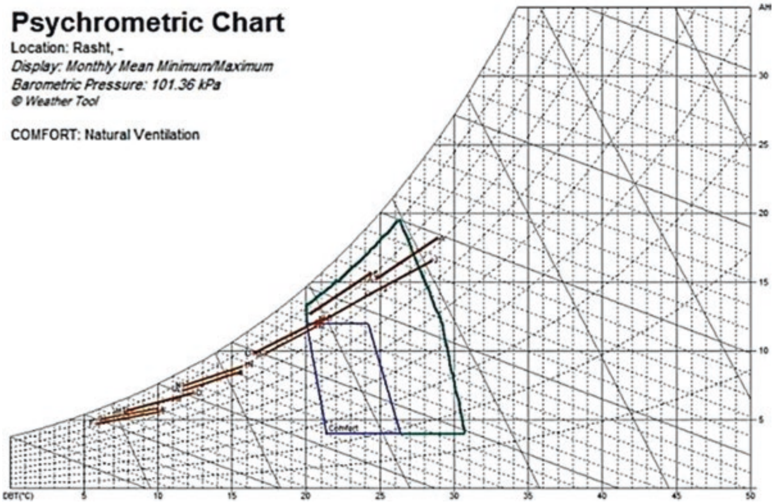


Fig. 1.1 "Givoni" bioclimatic chart of Rasht (Autodesk Ecotect Analysis 2011)

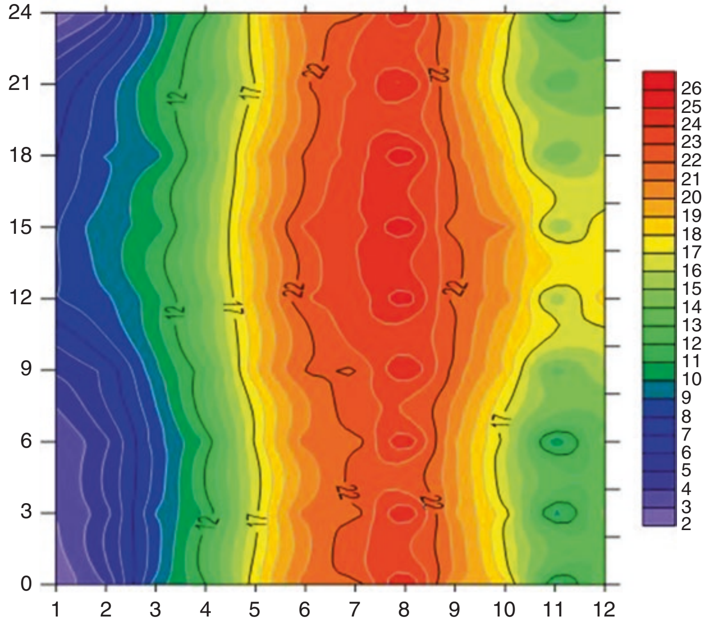


Fig. 1.2 Climatic needs in Calendar of Rasht

1.3.2 Climatic Region

The Guilan Province is located in the northern part of the country. Guilan weather is generally mild, caused by the influences of both Alborz Mountains and the Caspian Sea. This region has a humid temperate and Mediterranean climate with abundant annual rainfall and high relative humidity (between 40% and 100%), and its average temperature is 17.5 °C [26]. The weather data of Rasht, the capital city of the province, were utilized for the simulations as the representative of a moderate humid climate.

The latitude of Rasht is 37°2′ N and 49°6′ E; therefore, the corresponding sun path relevant to the latitude was drawn by solar tool software (Fig. 1.3) that helps designers determine sun location and shadow-casting conditions at any moment of the year. Figure 1.4 demonstrates the transfer of shadow need periods into the sun path diagram. From the shadow angles of a sun protractor (0–90°), the desired horizontal and vertical sunshade angles are estimated (in Fig. 1.5, the black line indicates the shading mask that must be considered in the sunshade design of south-oriented windows). As the proportional sizes of windows are already determined, the sunshade pattern is achievable. This procedure is repeatable for any window orientation.

Climatic data were obtained by the relevant meteorology station, and hourly data were taken from Meteonorm software, converted to wea. format, ready to be applied in the Autodesk weather tool 2011.

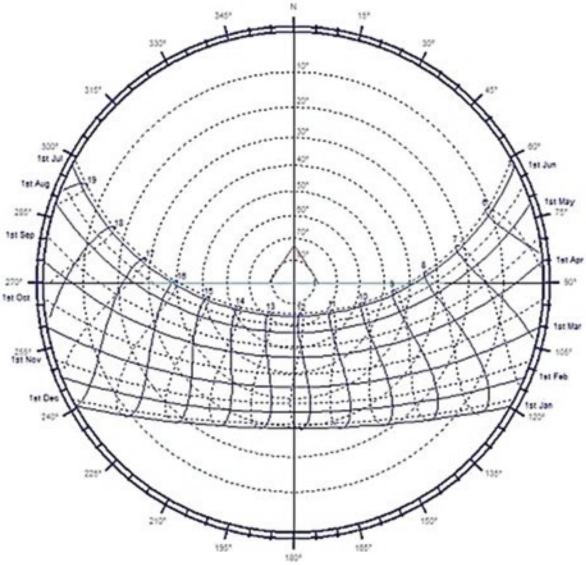


Fig. 1.3 Annual sun path in Rasht

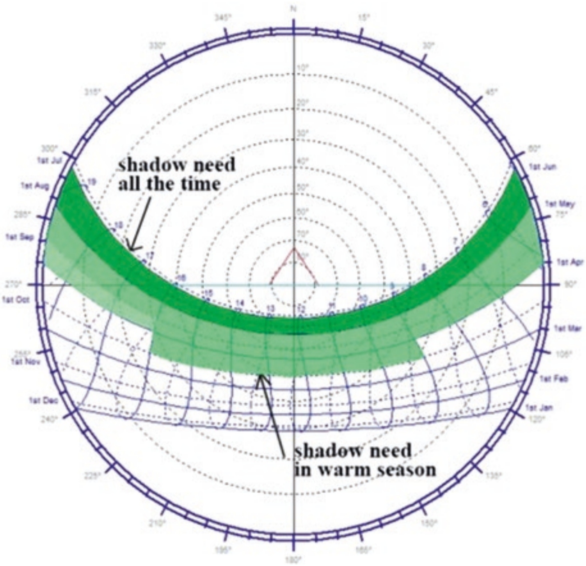


Fig. 1.4 Various shadow needs on the sun path

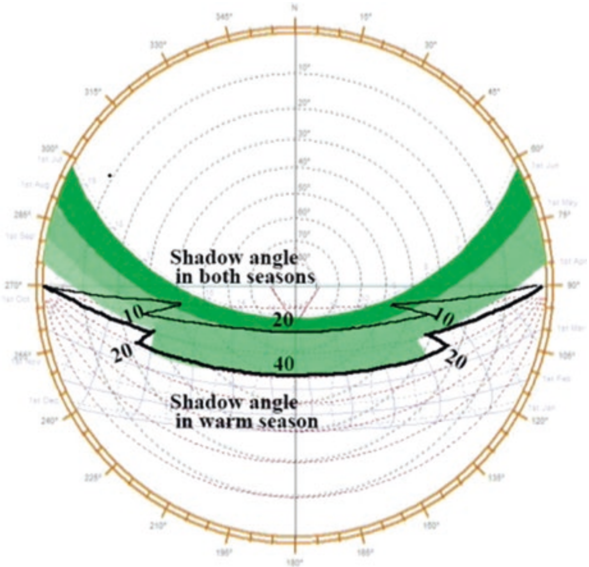


Fig. 1.5 Shadow angle for south-oriented window

1.3.3 Prefabricated Building Prototype

A case building is considered in accordance with architectural and structural considerations: rapidity and simplicity of assembly, expandability and flexibility, and compatibility with the environment. This typically designed residential building model has the dimensions 9.80 m in length and 5.60 m in width, with a total area of 55 m^2, equipped with bathroom, kitchen, technical room, and a multi-purpose space (Fig. 1.6). This model constitutes three attached modules, two types of 1.80 m × 4.80 m and 2.40 m × 4.80 m, which is the smallest configuration and is planned for occupation by a couple. Other larger alternatives, including four or five or more modules, are also feasible to satisfy the needs of larger families (see Fig. 1.7).

According to the recommended design strategies in this climate, the longitudinal axis of the building is oriented along the east–west direction to maximize heat gain in winter and heat loss in summer. Because natural ventilation is the other condition in the second zone to provide indoor thermal comfort, rather than shadow on the window surface, the Wind Rose pattern of the summer season in the city of Rasht was considered; the decided orientation is in line with the optimal opening location in the windward and leeward wall sides in the one-layer plan design of the modular buildings.

Many different parameters in window properties affect the thermal comfort of interior spaces. Except for the shading strategies, which were taken as the main

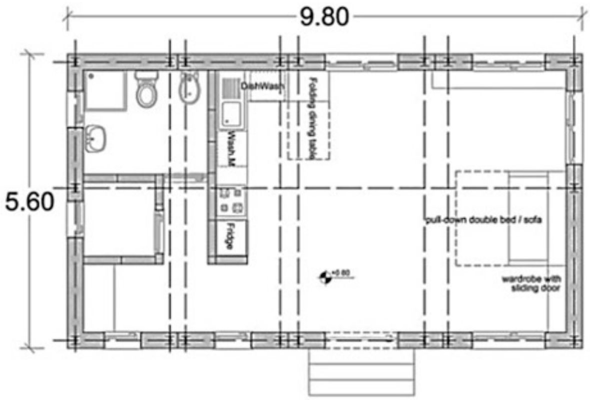
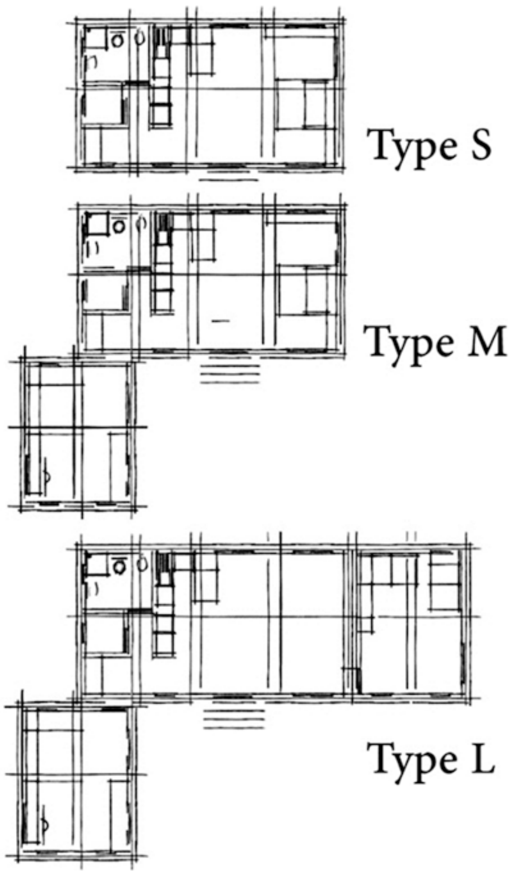


Fig. 1.6 Indoor space layout of prefabricated building

Fig. 1.7 Modularity of building types



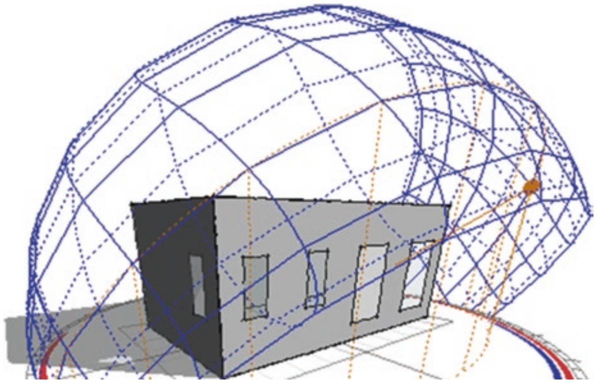


Fig. 1.8 View of prefabricated building model in the annual sun path, Rasht location (Autodesk Ecotect Analysis 2011)

variables, other features are kept identical (e.g., area, geometry, windows design, glazing area, and transmittance ratios).

1.3.4 Simulation Tool

The emergence of a large number of software programs has dramatically changed the manual methods of solar design, leading building engineers and architects to revise the fundamental principles/methods to adjust these with the novel capabilities; among them, Ecotect software has been utilized in various reliable applications in the field of solar studies. For example, Yang et al. [27], Dutta et al. [1], Aldali and Moustafa [28], and Jamaludin et al. [29] used Ecotect for the analysis of solar radiation effects on envelopes.

For the purpose of this chapter, Ecotect was used as the building performance tool, mainly because its pleasant interface makes it easy for application by architects. Simulations were conducted in Ecotect to evaluate the effects of various shading strategies on thermal comfort in a prefabricated building in a temperate climate.

Individual spaces are generated as divided areas in Ecotect, named “zones.” Further, annual and daily sunrays over the building are simulated to investigate shadow conditions on the glazing area (Fig. 1.8). Finally, simulations and evaluations can lead to providing shading design recommendations.

1.3.5 Shading Device Variables

Sunshades are the studied variable in this research, and the optimum range of other parameters was assumed according to the studies in the literature. External shadings operate up to 30% more effectively compared to internal shadings.

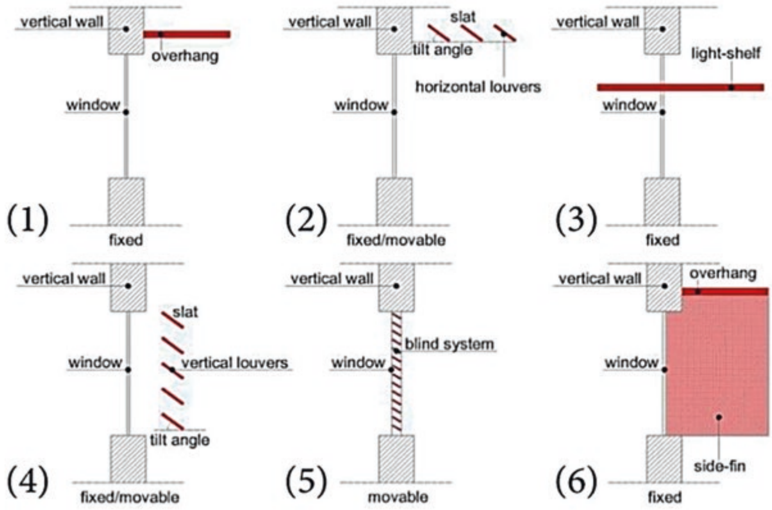


Fig. 1.9 Main shading types [31]

Horizontal external shading is generally recommended for south- and north-oriented windows whereas vertical shading is more appropriate for east- and west-oriented fenestrations [30].

The investigation of this study is limited to shading properties. Shading device types are categorized as (1) overhang, (2) horizontal louvers, (3) light shelf, (4) vertical louvers, (5) blind system, and (6) side fine (see Fig. 1.9) by Bellia et al. [31] in a review research of solar shading systems. In each category, the shape, depth, and length were varied and the shadow obtained on the glazing surface was investigated. The most common practical window types and sizes, which are adjusted to the modular panels, were considered in the analysis. Several configurations were explored to achieve the optimal solution for maximum internal thermal comfort. Because of the wall structure requirements (studs at the usual distance of 60 cm), 70 cm was considered for the panel width, and window dimensions are designated in three different heights and two different widths (Fig. 1.10).

1.4 Results and Discussion

On the basis of the shadow/sun need periods, dimensional and proportional characteristics of shading systems were obtained via Ecotect simulations because the shadow period need is not symmetrical with respect to the solstice. There are periods in warm seasons when shadow is needed (e.g., midday in September) whereas sun is preferred in the corresponding cold season (e.g., in March). This priority is embedded within the subject of climate. In a temperate climate in which humid

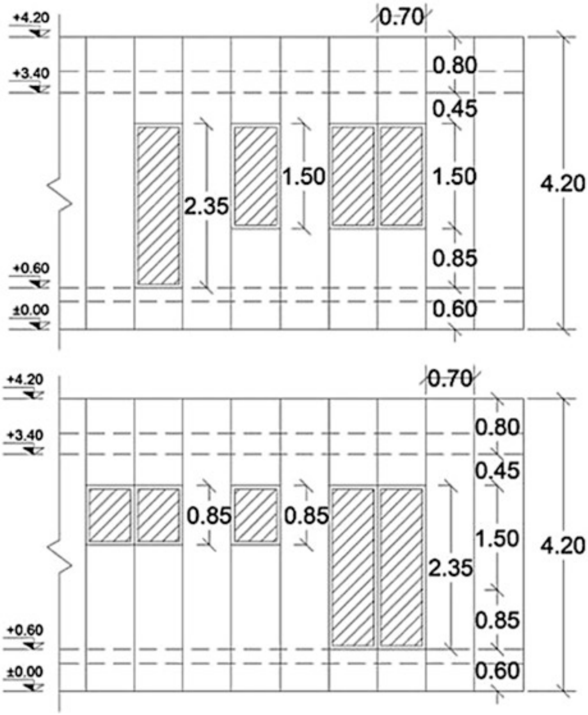


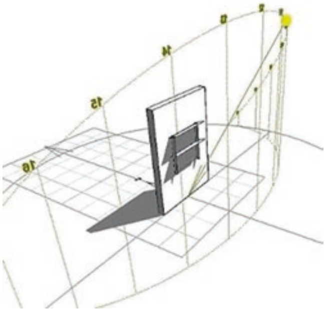
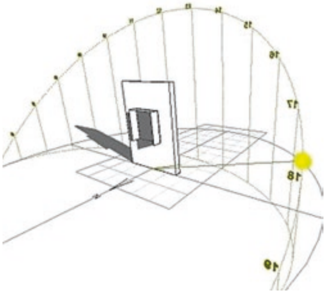
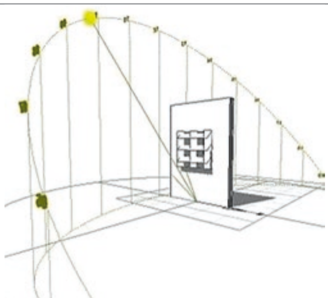
Fig. 1.10 Modular window prototypes

summers get uncomfortable, the priority of thermal comfort goes with the warm seasons. The other consideration in this study is to use the least variety and the most similarity in building elements (in size, geometry, etc.) to be in line with the nature of prefabricated construction. Furthermore, all the sunshades were assumed to be fixed; although movable shading provides more practical solutions, they require higher levels of technology and facilities that are probably unavailable in temporary, low-budget projects.

Window types were investigated in four main orientations. Despite the subtle difference of shadow needs between west and east orientations, the greater shadow need was considered as the dominant criterion to minimize variety and maximize homogeneity in the modular design. According to the shading mask, the required depth was attained for both horizontal and vertical shades; in the case of wider or higher windows, the acquired depth is broken into more than one element. Table 1.1 summarizes the results of simulations for all six window types in main cardinal orientations. For the aim of simplicity, type 1 modeling in the south direction is demonstrated.

On the south side, horizontal and vertical sunshades are needed at the distance of 70 cm. Thus, three, two, and one blades are required for 240 cm, 150 cm, and 85 cm windows, respectively. An angle of 20° allows keeping the shaded area in warm periods and avoiding it in cold seasons. However, no inclination for vertical shades is effective.

Table 1.1 Summary of shading characteristics in four cardinal directions

	Shading simulation for type 1	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
South		nH 2	nH 2	nH 3	nH 3	nH 1	nH 1
		dH 40	dH 40	dH 40	dH 40	dH 40	dH 40
		lH 170	lH 100	lH 100	lH 170	lH 100	lH 170
		aH −20	aH −20	aH −20	aH −20	aH −20	aH −20
		nV 2	nV 2	nV 2	nV 2	nV 2	nV 2
		dV 10	dV 10	dV 10	dV 10	dV 10	dV 10
		lV 155	lV 155	lV 240	lV 240	lV 90	lV 90
		aV 0	aV 0	aV 0	aV 0	aV 0	aV 0
North		nH 1	nH 1	nH 1	nH 1	nH 1	nH 1
		dH 40	dH 40	dH 40	dH 40	dH 40	dH 40
		lH 140	lH 70	lH 70	lH 140	lH 70	lH 140
		aH 0	aH 0	aH 0	aH 0	aH 0	aH 0
		nV 2	nV 2	nV 2	nV 2	nV 2	nV 2
		dV 40	dV 20	dV 20	dV 40	dV 40	dV 40
		lV 150	lV 150	lV 240	lV 240	lV 70	lV 240
		aV 0	aV 0	aV 0	aV 0	aV 0	aV 0
East & West		nH 3	nH 3	nH 5	nH 5	nH 2	nH 2
		dH 40	dH 40	dH 40	dH 40	dH 40	dH 40
		lH 155	lH 85	lH 85	lH 155	lH 85	lH 155
		aH +45	aH +45	aH +45	aH +45	aH +45	aH +45
		nV 3	nV 2	nV 2	nV 3	nV 2	nV 3
		dV 30	dV 30	dV 30	dV 30	dV 30	dV 30
		lV 155	lV 155	lV 240	lV 240	lV 90	lV 90
		aV +45	aV +45	aV +45	aV +45	aV +45	aV +45

nH number of horizontal sunshades, *dH* depth of horizontal sunshade (cm), *lH* length of horizontal sunshade (cm), *aH* angle of horizontal sunshade (°), *nV* number of vertical sunshades, *dV* depth of vertical sunshade (cm), *lV* length of vertical sunshade (cm), *aV* angle of vertical sunshade (°)

On the west/east sides, the incident ray angle, which is closer to perpendicular, allows the depth of the horizontal blades to be equal to the glazing height; this necessitates a greater number of both shades (Table 1.1). Also, an angle of 45° for both vertical blades (downward) and horizontal blades (clockwise) increases the efficiency of the shading system.

In the north orientation, the major challenge is focused on the warm season, because in the cold period the north side is not the subject of sun radiation in the Northern Hemisphere. In the required periods of the calendar, northern windows are protected by one simple horizontal on the top and two vertical blades on the sides (as the dimensions are determined in Table 1.1).

The overall advantages of this method include (1) providing the ability to control shadow and sunshine in a given period of a year and (2) allowing the design of different alternative shades; it also (3) enables the designer of high mass production projects (i.e., prefabricated buildings) to generalize the analysis of a limited number of fenestration systems to a large number of cases.

1.5 Conclusion

On the basis of the results of this study, although application of shading improves thermal comfort conditions, none of the simulated strategies was sufficiently effective to satisfy the absolute thermal comfort criteria. Therefore, solar shading should be used in line with other strategies to attain thermal comfort inside a building. However, considering temporary modular buildings, the geometrical visual guidelines for a pattern to design their fenestration system in a sample latitude are provided. Obviously, the shape and form of sunshades in any individual project are finalized by the specific aesthetic, construction, and economic issues.

Further studies are recommended for modular buildings in other climatic conditions throughout the world at lower or middle latitudes where shading is an essential passive strategy to improve the thermal performance of buildings. Additionally, considering other parameters as variables provides more comprehensive solutions in terms of climate-responsive design.

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