Modelling Daylight in Adjacent Spaces of the Courtyard under Clear Sky Conditions

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Abstract

This paper investigates daylight performance in courtyard buildings with focus on how different design configurations affect daylight availability and potential of glare in the courtyard's adjoining spaces. The study is conducted under clear sky conditions of the UAE. The analysis of the performance variables in question depended on Climate-based Daylight Metrics (Daylight Autonomy variations). The method relied on computer simulations using DAYSIM software under Rhino 3D modeler Interface. The study analyzed daylight penetration into the adjacent spaces with varying window-to-wall ratio (WWR from 40-100%) using several metrics: Daylight Autonomy variations (DA, sDA, DA_{Con}, DA_{max}) and Useful Daylight Illuminance (UDI). It concludes with prediction models and design guidelines on the optimum courtyard design and proper sizing of the courtyard's space and adjacent zones for improved daylight availability and visual comfort.

Keywords: *climate-based daylight modeling, daylight simulation, courtyard, clear sky.*

Introduction

The courtyard in hot arid climates served as a cool air collector at night and a shade provider during the daytime. Acting as the central space of a building and the heart for occupant activities, the courtyard provides a direct link to the outdoor environment while introducing daylight into the adjacent spaces. There is also lack of evidence of their performance concerning daylighting, especially in clear skies conditions. The majority of the previous studies carried out on the environmental aspects of the courtyard examined its thermal performance, energy analysis, and solar shading and exposure (Aldawoud, 2008; Aldawoud & Clark, 2008; Muhaisen, 2006). Other studies investigated daylight availability in atria buildings in locations with overcast skies. The gap of needed research that help predict daylight availability under desert climates (with clear sky conditions) formed the main motivation behind this study. There is also a high potential for improving the performance of the courtyard in the clear sky conditions when its design is combined with other bioclimatic solutions based on previous investigations by the authors in different building configurations (Al-Sallal & Dalmouk, 2011; Al-Sallal & Abu-Obeid, 2009; Al-Sallal & Ahmed, 2007), for instance addition of window shading elements (e.g.,

window screens, light shelves, bio-shaders, awnings, arcades), landscaping elements in the courtyard space (e.g., trees, plants), and/or a shading fabric to cover the courtyard itself (e.g., toldo). These added elements have not been tested yet in the current work but they are considered in the ongoing project in which this paper is part of.

Theoretically, every climate would require a unique design to achieve an optimum performance; (Moore, 1993). How daylight performs in courtyard buildings is a function of daylight availability in the locality and the building design that affect its penetration (Muhaisen, 2006). While the availability of daylight depends on sky conditions, penetration of daylight to the interior depends on the building and its courtyard geometrical designs. Whichever the case, the courtyard is an architectural element that should take full advantage of the available daylight to enhance the luminous indoor environment for optimum human performance.

Method

To investigate in detail how daylight behaves in the courtyard and the spaces adjacent to it, wide-ranging simulation cases were conducted. The Climate Based Daylight Metrics (CBDM) method of calculation was selected due to its high potential to offer a holistic and more reliable results compared to the traditional methods that are dependent on limited dates/hours representing the average or extreme conditions of the year. The daylight simulation software "DIVA-for-Rhino" was used to simulate detailed daylighting calculations in the courtyard and its adjacent spaces (DIVA, 2018). It is a DAYSIM plug-in that is incorporated into 3-Dimensional GUI to accurately calculate daylight performance in simulated spaces using RADIANCE simulation engine, Daylight coefficient and Perez sky models (Reinhart, 2009).

The main function of the adjacent zones was considered as office spaces. The calculations were based on achieving a target illuminance level of 400 lux or more, as recommended by the IES lighting handbook for offices. The location tested was that of Abu-Dhabi, UAE with latitude 24.5°N and longitude 54.4°E. Parameters considered when defining the variables affecting the design of the courtyard were the courtyard's geometry (length, width and height), building orientation, surface reflection (in the courtyard and the space adjoining it), window-to-wall ratio of the courtyard's windows (WWR = 40-100 %) with no shading. The surface reflectance

values of the office space were defined based on the recommendations by IESNA for office use (DiLaura et al., 2011) (Table 1). The glazing was specified as clear double-glazed with 79% transmittance.

Table 1: Reflectance values of the indoor surfaces used in the study, based on IESNA specifications.

Layer	Material Reflectance Value
Ceiling	≥ 90
Floor	≥ 20
Wall	≥ 60

Courtyards in buildings can be found with many shapes and sizes but the square and rectangle shapes are the most dominant. The shape (either square or rectangle) was identified as the first variable for the courtyard geometry. The second variable was to define the dimensions in terms of length, width and height. A side length of 4 meters was considered as the minimum size of a reasonable small courtyard in a medium size building. It was used as a modular unit to size all courtyard cases evaluated in the study also. Hence, the first square-shaped courtyard was defined to have 4m×4m×4m dimensions; which is equivalent to (1:1:1) ratio. The sizing of the other square-shaped courtyards was then a representation of the ratios defined in Table 2, Left column. The rectangle shape courtyard started by doubling one of the sides of the square with the ratio of (1:2:1) and the longer edges facing the north/south orientations. In a similar manner, the sizing of the other rectangle-shaped courtyards was done (Table 2, right column). The orientation that was applied for the rectangular courtyard's cases faced North/South for the long sides based on previous recommendations by a previous study (Muhaisen, 2006). East/West orientations were excluded only at the current stage of this research considering that such orientation could cause direct sunlight into the rooms and occupants' eyes due to the low altitude sun angles; which could lead to increased levels of heat gains and glare. It is planned though to test other orientations including the intermediate ones (i.e.; NE, NW, SE, SW) in subsequent stages of the research project in which this paper is part of. The courtyards with the identified configurations shown in Table 2 were the ones simulated in the study. Yet, the method also demonstrates in a later stage how to interpolate between the produced results to predict the performance of other courtyard configurations. Each individual case of the courtyards defined in Table 2 was simulated separately at the center location of a square building (36m×36m). The reason for this size was to detect the admitted daylight in as much of the room depth as possible and calculate the percentage of the floor covered by adequate daylighting levels throughout the year.

Table 2: Sizing Ratios of Simulated Courtyards

Square Shaped (W:L:H)						Rectangular Shaped (W:L:H)			
1:1:1	2:2:1	3:3:1	4:4:1	6:6:1		1:2:1	2:4:1	3:6:1	4:8:1
1:1:2	2:2:2	3:3:2	4:4:2	6:6:2		1:2:2	2:4:2	3:6:2	4:8:2
1:1:3	2:2:3	3:3:3	4:4:3	6:6:3		1:2:3	2:4:3	3:6:3	4:8:3

Table 3: Investigated Courtyards Forms

	4×4	8×8	12×12	16×16	24×24	4×8	8×16	12×24	16×32	
1 Floor										
2 Floor										
3 Floor										

Each of the defined courtyard sizes (Tables 2-3) was simulated with three different height cases: 1, 2, or 3 floors (Fig.1-2), a reasonable height range for a medium-size public building.

Figure 1: Section Drawings through Simulated Configuration of Courtyard (8×8) with WWR 100%.

The simulated cases included windows on the central courtyard walls only; (no windows on the other walls); with two WWR scenarios: 40% and 100%. The method also demonstrated how to predict the performance of other WWR configurations, based on interpolation of the results.

Figure 2: Section Drawings through Simulated Configuration of Courtyard (8×8) with WWR 40%.

The boundary conditions can be outlined as follows:

- The size of the indoor space adjoining the courtyard extends from the boundary wall of the courtyard to the 36×36m building's boundary. This size is determined for a midsize public building for office, educational, or commercial use.

- The building height ranges from 1 to 3 floors, for the same reason as above.
- The courtyard's size was made proportionate to the building size reaching to a maximum of 24×24m due to climatic reasons.
- The longer sides of the rectangle-shaped courtyard were limited to North/South orientations to reduce heat gains and glare.

Figure 3: DA/sDA isocontours of the square-shaped courtyard configurations with 100% WWR.

Figure 4: DA/sDA isocontours of the square-shaped courtyard configurations with 40% WWR.

percentage values of the space area along with visual representations of the DA distribution in the space shown in isocontours maps. The Isocontours maps of the space make it easy to identify different boundaries of daylit areas. For the spatial daylight autonomy (DA/sDA) this boundary line corresponds to the area where 50% of the occupied time is receiving daylight levels equal or above the target illuminance, anything below this boundary line in the green blue shade of the legend is considered underlit, it can also be expressed as $DA/sDA_{(400lux)} 50\%$. Figs. 3 and 4 show the DA/sDA isocontours of the square-shaped courtyard configurations with WWR=100% and WWR=40% respectively. The isocontours of the other variations of DA (i.e., DA_{Con} , DA_{Max} and UDI) are shown in Figs. 5-8. DA/sDA is as an incremental method while DA_{Con} is a continuous method. What is observable in the DA_{Con} Isocontours is that the boundary of the daylit area is not as sharp as the case in DA/sDA. This is due to the partial credit given to sensor nodes that are not fully saturated with daylight, but do receive some daylight contribution. DA_{Max} Isocontours represent areas indicated by magenta color as areas with high potential of visual discomfort and glare (Fig. 6). This area receives ten times or more than the defined target lux; in this case the area is receiving more than 4000 lux. The useful daylight illuminance ($UDI_{100-2000lux}$) for WWR=100% and WWR=40% are shown in Figs. 7 and 8, respectively. The other (non-useful) bins (i.e., $UDI_{<100lux}$ and $UDI_{>2000lux}$) represent the hours when there is a lack of sufficient daylight and the hours when there is an oversupply of daylight that can lead to visual or thermal discomfort.

Figure 5: DACon isocontours of the square-shaped courtyard configurations with 100% WWR.

Results and Discussion

The results of the Daylight Autonomy (DA) variations in relation to the simulated cases are represented as

Figure 6: DAMax isocontours of the square-shaped courtyard configurations with 100% WWR.

Figure 7: UDI100-2000 isocontours of the square-shaped courtyard configurations with 100% WWR.

Figure 8: UDI100-2000 isocontours of the square-shaped courtyard configurations with 40% WWR.

Analysis

The values of DA/sDA are further analyzed to understand their representation in relation to the courtyard's shape, size, height and WWR. In general, what was evident from the DA/sDA Isocontours maps is that the daylit area is almost symmetrical in all directions with circular shape boundary in the square shaped courtyards with 100% WWR and petal shape for 40% WWR, and increases in similar pattern when the courtyard size was increased. Similar behavior applies to the rectangle shape courtyard. This is in terms of daylit area shape behavior, but when looking at DA_{Max} Isocontours what is evident is that the area of the adjacent space facing north has minimum to almost no potential for visual discomfort. Bar charts were generated to further understand the behavior of DA/sDA in the different courtyards configurations (Figs. 9-10). The general observable trend is that DA/sDA value in smaller courtyards sizes especially in the lower floors tends to be very low and increases significantly to higher value as the height of the floor increases. This high difference in values diminishes as the size of the courtyard increases. What is also evident from the bar chart is that when the building is in a single floor prototype the DA/sDA value is higher than that on the highest floor on the other prototypes, the reflected light coming from the courtyard ground causes this. Therefore, attention should be given to use a suitable ground surface since it contributes to altering lighting in the adjacent spaces.

To further understand the DA/sDA behavior in all simulated courtyards a relationship between the courtyard volume — the Aspect Ratio method $AR=L \times W/H^2$ adopted in Dekay (2010), the building height configuration and the DA/sDA value was established, for both the square and the rectangle shaped courtyards. This

relationship was expressed graphically in charts for all evaluated configurations.

Figure 9: Impact on DA/sDA when increasing courtyard size with 100% WWR.

Figure 10: Impact on DA/sDA when changing courtyard shape from square to rectangle with 100% WWR.

Fig. 11 shows a sample of the produced charts depicting the relationship between the courtyard aspect ratio (AR) and DA/sDA value for the square-shaped courtyards with a single floor building. These charts can help architects to design buildings with sufficient and comfortable daylighting in the adjacent spaces of the courtyards.

Figure 11: Relation between courtyard aspect ratio (AR) and DA/sDA value in square-shaped courtyards with a single floor building.

The governing equations of the relationship between DA and AR for all variants of the DA were established to give the designer freedom of choice to either use the charts or

the equations to size the desired courtyard. The generic form of this equation is expressed as:

$$DA = c \ln(AR) \mp b \quad (1)$$

Where c and b are constants depending on the courtyard and building design configurations (courtyard shape, floor, building total number of floors) and $\ln$ is the natural logarithm function of the aspect ratio (AR) of the courtyard. For the single floor building with a square courtyard, the DA equation is expressed as:

$$DA = 24.4 \ln(AR) \mp 15.9 \quad (2)$$

Another important outcome of this research are the tools produced to help architects in minimizing the effect of direct sunlight and potential glare such as in museums when high levels of light might damage artefacts. After finding the aspect ratio based on the desired target (depending on DA/sDA or DA_{Con}), the designer can use the DA_{Max} charts or the equations to predict the percentage of the total space area receiving illuminance levels higher than 4000 lux. For example, if the AR was determined as 15 from the previous section, the DA_{Max} will be 30% (as shown in Fig. 12), meaning that 30% of the space will have a potential to receive direct sunlight or excessive daylight ten times of the desired target illuminance (400 lux).

Figure 12: Relation between courtyard aspect ratio (AR) and DA_{Max} value in square-shaped courtyards with a single floor building.

As stated earlier, certain relationship in terms of the variables that influence the value of the desired daylight level in the design of the courtyard and the adjacent space to it was created. This was reflected as a scenario or a set of steps to be followed by the designer based on courtyard shape (square and rectangle) and building height configuration (single, two and three floors), using different charts or equations derived from regressions of the derived data. These charts and equations can be added to building codes to help architects to define appropriate courtyard sizing based on chosen target level of DA/sDA and DA/sDA other variations.

Conclusion

The attained findings from the extensive simulations were used to develop mathematical models of relationships between design variables and their effect on daylight autonomy performance measures; which at the end created a set of design tools for optimizing courtyard design including graphical representations and formal equations. The tools generated can be very useful in promoting the use of courtyards as an important element for deep daylight penetration into buildings. They can be used to optimize the sizing of courtyards for better daylight performance under clear sky climates.

The investigations have revealed a number of important findings:

- The square shaped courtyard proved to be more effective in terms of daylight admittance and behavior.
- Reducing the WWR proved to enhance the results in terms of visual comfort, as this was evident when comparing the DA_{Max} isocontours of smaller and larger values of WWR.
- The area of the adjacent space facing north is the most favorable for visual comfort.
- The general observable trend is that CBDM values in smaller courtyards especially in the lower floors tend to be very low and this effect increases significantly to higher values as the height of the floor increases. This high difference between values diminishes as the size of the courtyard increases.
- Courtyard ground reflectance contributes to altering light levels into the adjacent spaces; this is observable when comparing the DA results of a single floor building to the values on the top floor of a building with similar courtyard properties.

Future research should investigate other courtyard design factors including other building and courtyard geometries, other orientations including the intermediate ones, additions of courtyard and window shading devices (e.g., toldo, window screens, light shelves, bio-shaders, awnings, arcades), and landscaping elements in the courtyard space (e.g., trees, plants) as these factors could contribute in improving daylighting performance in clear sky conditions. Parallel investigations that help create design tools for optimized courtyard daylighting in other climatic conditions is highly recommended.

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