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The Effect of Wind Tower Design Parameters on Its Daylighting Performance in a Tropical Hot and Humid Climate

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Abstract. The use of daylight in buildings is known to have benefits in both reducing energy consumption and improving human comfort and health. Wind towers are traditional architectural components used for providing natural ventilation and cooling in hot and dry climatic zones. To investigate this architectural component's daylighting performance, an experiment was designed to evaluate different wind tower configurations under tropical hot and humid conditions. A generic room was modeled, and a total of 18 configurations, with varying wind tower design parameters such as height, length, and placement were tested. The modeled room with the wind tower configurations was also tested in three different orientations. Daylighting simulations were performed using ClimateStudio (Solemma LLC) to examine lighting parameters such as illuminance levels under CIE overcast sky conditions, and a modified spatial daylight autonomy (msDA). Weather data from Puerto Rico was used to run the simulations. The obtained performance data is examined using linear regression statistical analysis and the correlations between the tested parameters and the daylighting performance are described. Results showed that the wind tower design significantly impacts its daylighting performance. The height had the most significant effect and contributed to most of the variance in the observed daylighting metrics.

Keywords: Wind towers · Daylighting · Daylight metrics · ClimateStudio · Hot and humid climate

1 Introduction

The use of daylighting has been associated with benefits in terms of energy consumption, human health, visual comfort, and visual performance. Peak daylighting potential occurs at peak electric load times. Since lighting can be 20–40% of a building's electric loads, minimizing electric lighting use during peak cooling times can reduce the peak electric load of a building by nearly this amount [1]. Researchers have suggested that health is improved when we are immersed in the daily fluctuations of light and are visually connected to views and outdoor conditions [2]. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eye strain. Some researchers have also pointed out that daylight is necessary for optimal visual performance. In terms of relative intensity, sunlight provides the most consistent and fullest

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spectrum of colors for the human eye [3]. Daylight provides high illuminance and permits excellent color discrimination and color rendering. These two properties mean that daylight provides the condition for good vision [4].

The considerable energy consumption attributed to buildings and the increasing requirements for healthier and more comfortable indoor environmental quality has led researchers and designers to consider different natural ventilation and daylighting strategies. Wind towers, also called wind catchers, are architectural components traditionally used in hot and dry regions to capture fresh air from outside and direct it towards the interior spaces. For centuries, this building element was able to produce comfortable conditions in harsh climates without the need for machinery or energy consumption [5]. Although it is not its main function, this roof-mounted device has also been considered by some researchers as a potentially effective daylighting strategy [6–9].

If properly studied and designed, wind towers have the potential to function as both a natural ventilation and daylighting architectural solution. However, the existing research on this component is limited in its applicability within the practice of architectural design. New research is warranted to assess whether wind towers can be used simultaneously as an effective natural ventilation and daylighting strategy in tropical hot and humid climates. The purpose of this study is to further develop the understanding of wind towers by investigating the effect of wind tower design parameters on their daylighting performance.

2 Background

Geometric and design parameters that affect the natural ventilation performance of wind towers have been identified. The height, the cross-section (plan shape and area), the shape of the roof, the internal partitions, the amount and placement of openings, and the use of louvers, dampers, and diffusers are determinant design parameters relating to the wind tower [5, 10, 11]. Research into the effect of external building parameters is less developed. In this area, only the building roof and upstream objects have been investigated [10]. Research on wind tower daylighting performance is considerably less when compared to existing work regarding their cooling and natural ventilation effect. The following paragraph presents a review of the investigations conducted to assess wind tower daylighting performance.

A sensitivity analysis was conducted by Pratiwi et al. [6] on the daylighting performance of wind towers used in a generic isolated room based on three design parameters; the number of gratings (a type of vertical louvers), the "chimney" (by chimney it is understood the wind tower opening) height and its interior surface reflectance value [6]. This analysis was performed by observing the effect of the tested parameters on the Average Daylight Factor (ADF) using the Honeybee tool in Grasshopper. The statistical analysis showed that the three design variables have a significant impact on the daylighting performance of the tested wind towers, the "chimney" height being the most relevant. It was found that by increasing the "chimney" height and the interior reflectance the daylighting levels are increased as well. Increasing the number of gratings in the tower opening reduced the daylighting levels. Other daylighting studies focused on field study measurements of existing wind towers [7, 8]. Subsequent experiments were carried out by varying the internal reflectance values of the measured wind towers. Tests with higher reflectance values were found to be the best in distributing higher illuminance levels. An additional study evaluated wind tower daylighting performance and compared it with two other daylighting systems used in the traditional architecture of the United Arab Emirates [7]. On-site measurements and simulations using Radiance were used to compare the three daylighting systems. This study is limited to a comparison of the wind tower performance with two other traditional daylighting systems. Thus, the wind tower design parameters were not evaluated.

Apart from the studies mentioned above, no other research was found on the topic of wind tower daylighting performance. This highlights the need for additional research in this area. The available knowledge on wind tower performance is not enough for it to be effectively implemented as a passive design strategy for both natural ventilation and daylighting. Parameters that have been identified and studied for their effect on natural ventilation have yet to be studied in terms of daylighting performance. It could be hypothesized that wind tower parameters not only affect its daylighting behavior but might also create conflicting relationships to optimize for both passive design strategies, such as obtaining better daylighting at the expense of natural ventilation, or vice versa.

3 Methodology

This study investigates a proposed one-sided wind tower used to cross ventilate a generic room in Puerto Rico. An experiment was designed to assess the effect of the wind tower design parameters on their daylighting performance. The influence of the wind tower parameters is observed in their contribution to the modified spatial Daylight Autonomy (msDA) and the mean illuminance levels (lux) of each configuration. Regression statistical models are used to evaluate the correlation between the wind tower design parameters and the obtained daylighting metrics.

3.1 Configurations Geometry

As shown in Fig. 1, the design parameters assessed in this study are the wind tower height, length, and placement relative to a rectangular room. Three variations in height and length were tested in regular increments of four feet (8’-0”, 12’-0”, and 16’-0”). The height of the tower is being increased but the opening height remains fixed at three feet (3’-0”) in every configuration. A 24’-0” by 30’-0” by 12’-0” feet room in which the wind tower was placed was modeled. The wind towers were tested being placed centered on the short side of the room (placement option A), as well as on the long side of the room (placement option B). Since the wind tower is a natural ventilation device, the outlet windows were modeled as openings without glazing. The space in placement option A included two windows ten feet and nine inches wide (10’-9”) by five feet (5’-0”) high, and a window to wall ratio (WWR) of 37.3%. The space in placement option B included two windows thirteen feet and nine inches wide (13’-9”) by five feet (5’-0”) high, and a WWR of 38.1%. The images in Fig. 2 illustrate the dimensions of the modeled test room.

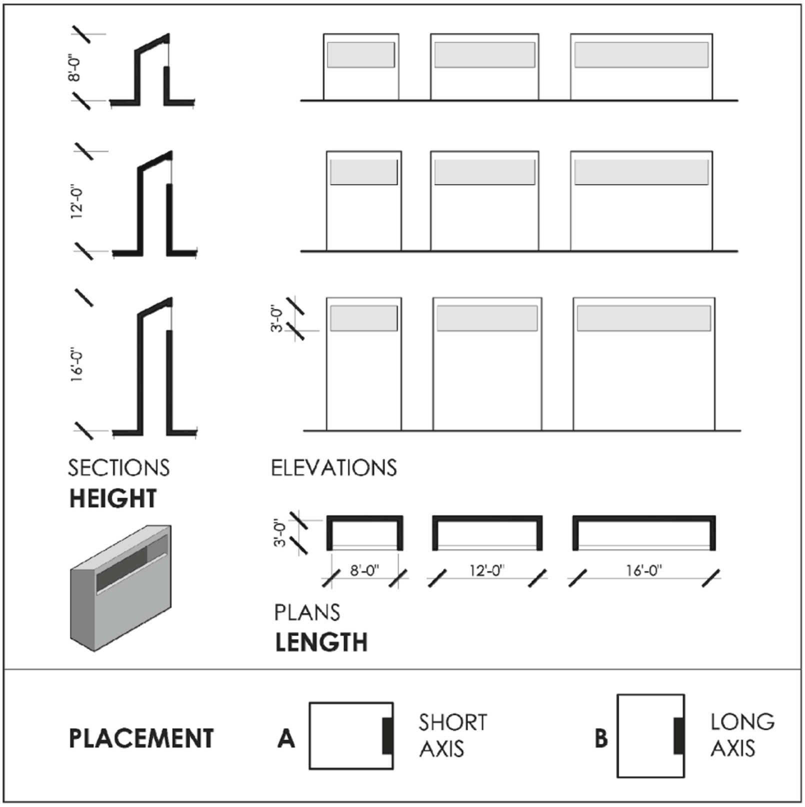

Fig. 1. Tested wind tower parameters

By combining the different variances in the wind tower design parameters, a total of 18 configurations were generated. The configurations were compared against two base models for each placement option without the wind tower. A conventional nomenclature was established to help identify each configuration. The configuration without the wind tower for placement option *A* was labeled **BASE MODEL-A**, and the model without the wind tower for placement option ***B*** was labeled **BASE MODEL-B**. Every model name contains the placement option of the wind tower (***A*** or ***B***), the height (***8H***, ***12H***, or ***16H***), and the length (***8L***, ***12L***, ***16L***). For example, model ***A-8H8L*** refers to the model with placement option A, with eight feet (8'-0") high and eight feet (8'-0") long wind tower. Figure 3 shows a matrix containing all the configurations and the base models with their respective names.

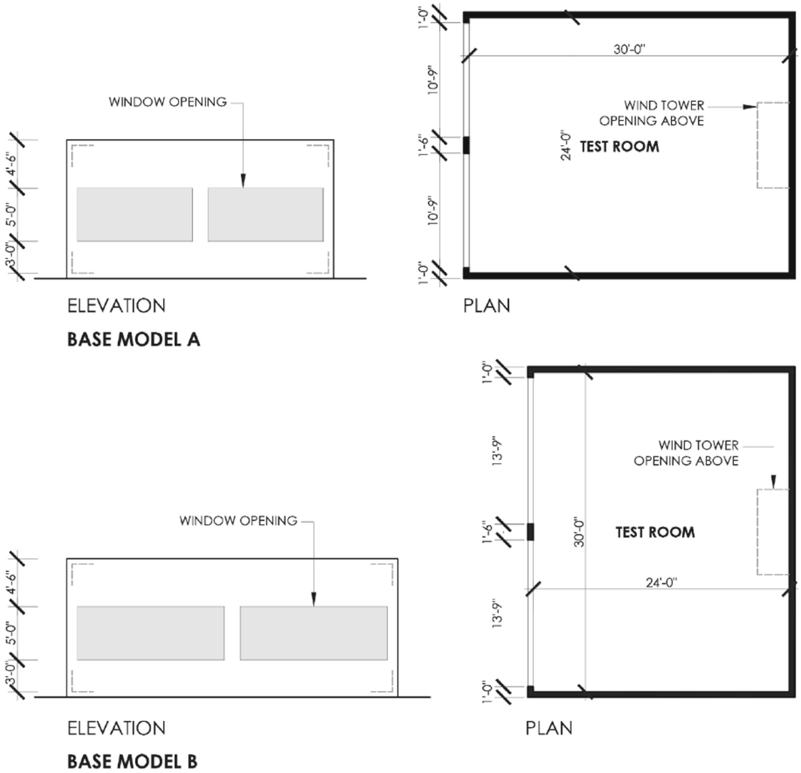

Fig. 2. Model test room dimensions

3.2 Daylighting Simulation

The daylighting simulations were conducted using ClimateStudio (SolemmaLLC) to evaluate a modified spatial Daylight Autonomy (msDA) and the illuminance levels on all room configurations. The conventional sDA metric used to confer LEED daylight credits is defined as the percentage of floor area where 300 lux is achieved for at least 50% of standard operating hours on an annual basis. Therefore, the ClimateStudio plugin for Rhino, through the Daylight Availability workflow, conducts a dynamic annual daylighting simulation from the input weather data with a Radiance-based engine to obtain the sDA value. The sDA metric in ClimateStudio was modified to reflect the floor area that achieves at least 300 lux for 99% of standard operating hours (8:00 am – 6:00 pm) on an annual basis, which represents an almost perfect daylight autonomy. For the msDA simulations, every configuration was tested at three different orientations. All configurations were simulated facing three orientations: N30°E, N60°E, and N90°E (see Fig. 4). These alignments respond to the prevailing wind directions of Puerto Rico. The variance in orientations also considers possible design limitations such as site geometry and orientation.

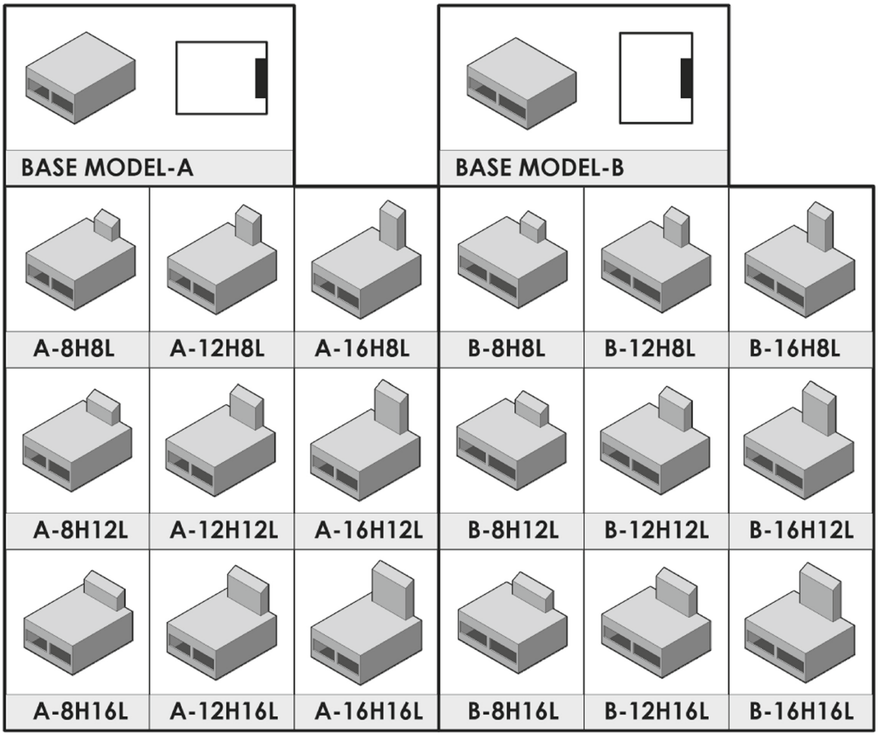

Fig. 3. Configuration matrix with model nomenclature

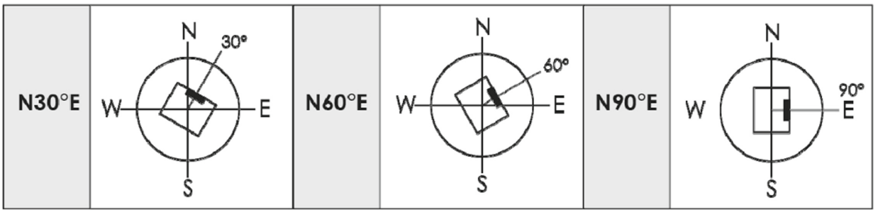

Fig. 4. Tested orientations for msDA simulations

The mean illuminance levels (lux) were evaluated under CIE Overcast Skies using ClimateStudio's Point in Time Illuminance workflow. The simulations were done at 12:00 pm on March 21. Overcast skies allow to evaluate the different configurations without considering the orientation and direct light entering the space due to the sun position under clear skies.

For both the msDA and illuminance level simulations the interior surface reflectance is 0.85 for ceiling, wind tower interior surfaces and roof, 0.6 for the walls; and 0.45 for the floor. The grid for the simulations consisted of 154 sensors spaced in 2 feet by 2 feet grid and at 2.5 feet height above floor level.

3.3 Data Analysis

To examine the obtained data a statistical analysis using linear regression was performed on an Excel sheet. The msDA percentage and the mean lux levels for each tested configuration were observed as dependent variables in the regression models. The model that considers the msDA value as the dependent variable uses height, length, and orientation as the independent variables. The wind tower placement options were considered in two separate regression models. The second set of regression models used the mean illuminance (lux) level as the dependent variable and only the height and length parameters as the independent variables. The influence of the parameters is observed in the Correlation Coefficient (CC), the R square, and the P-value of each correlation. The CC describes the strength of the relationship between the relative movements of two variables. It is a value between -1 and 1, whereas a value below 0 describes a negative correlation, and a value higher than 0 describes a positive correlation. A negative correlation refers describes a relationship where an increase in the independent variable causes a decrease in the dependent variable. In a positive correlation, an increase in the independent variable causes an increase in the dependent variable. The R square value represents the proportion of the variance in the dependent variable that is explained by the independent variable. The P-Value indicates the statistical significance of the results. The commonly used value of 0.05 is used as the threshold to determine statistical significance.

4 Results

The msDA results from the dynamic annual simulations under the three different orientations are shown in Figs. 5, 6, and 7. The results are shown in the percentage value of the msDA and floorplan view for every configuration, including the two base models. The floor plan view shows where the msDA achieving 300 lux during 99% of the operative hours on an annual basis was obtained. Figure 8 illustrates the mean lux levels obtained for every model. Although the illuminance levels were calculated for each data point within every configuration, the results are expressed as the mean value between the 154 data points. Each configuration is labeled according to the described nomenclature. The data shown in the graphs for the resulting msDA and mean illuminance levels were utilized to create the regression models.

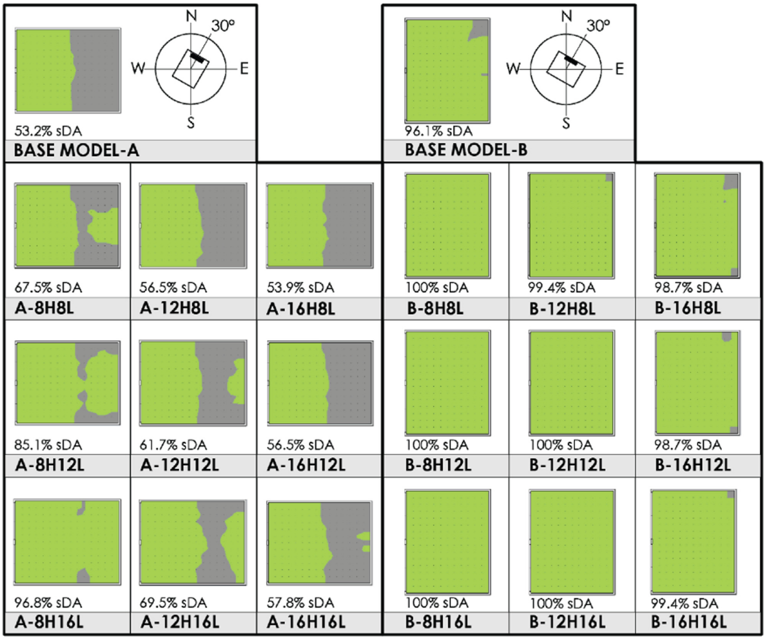

Fig. 5. msDA results for N30°E orientation. The green area shows msDA.

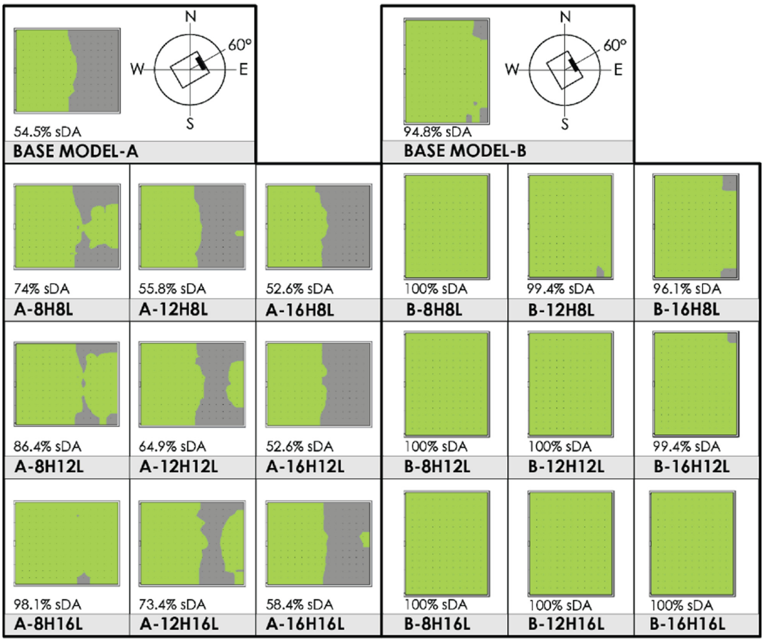

Fig. 6. msDA results for N60°E orientation. The green area shows the msDA.

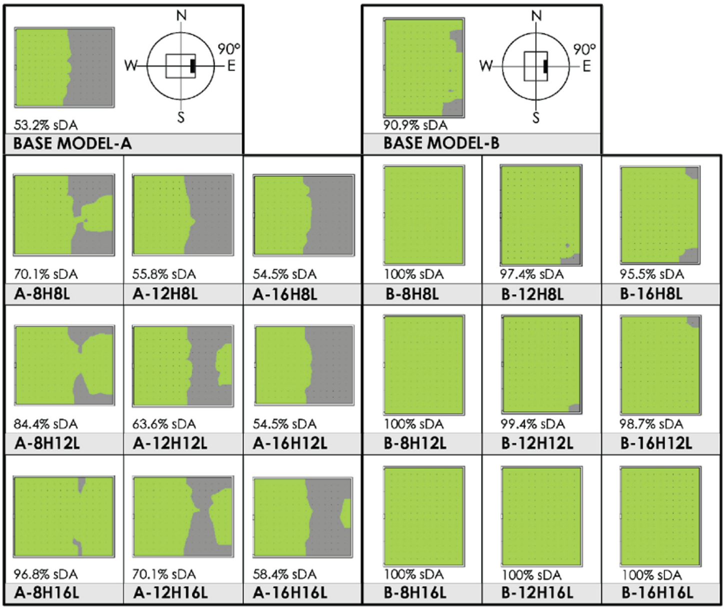

Fig. 7. msDA results for N90°E orientation. The green area shows the msDA.

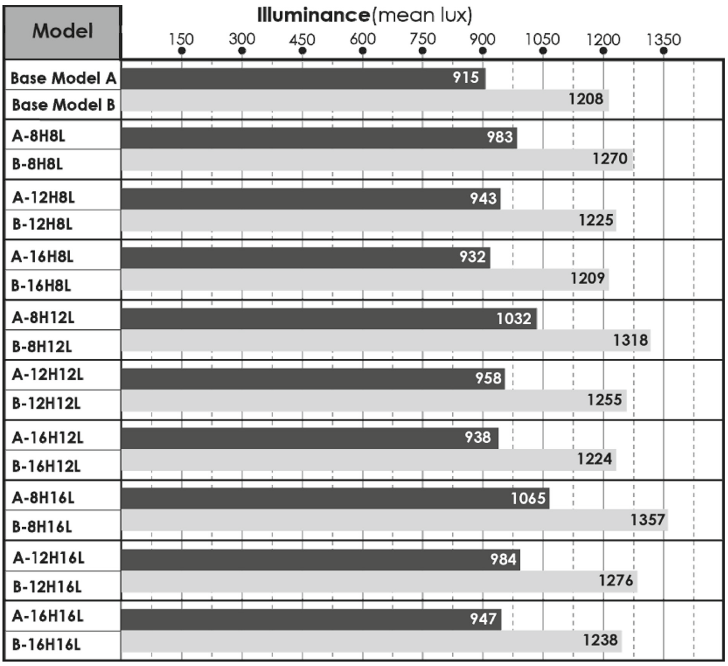

Fig. 8. Mean illuminance levels (lux) under CIE overcast skies

5 Discussion

The shorter and wider wind towers tend to provide higher percentages of msDA, meaning that they improve the distribution of acceptable daylighting levels throughout the whole room area. A trend in the data was observed whereby increasing the height of the wind tower led to decreasing msDA and mean lux levels. For example, in the models with placement option A, at a set wind tower length of 12 feet, an increase from 8 to 12 feet in height decreased the msDA by roughly 20% in all three orientations. The change from 12 to 16 feet height does not display a decrease as drastically, as only a 5–12% (across the different orientations) loss of msDA is observed across the different orientations. The length parameter follows a similar trend in reverse, as it appears that longer wind towers increase msDA. The models with placement option A with a 12 feet high wind tower display an increase of 5.2–9.1% msDA by increasing the length from 8 to 12 feet. Further increasing the length to 16 feet increases the msDA levels by 7.8–8.5%. The effect of the length appears more drastic in the shortest wind tower configurations, as increasing the length of the 8 feet high wind tower from 8 to 12 feet produces a 14.3–17.6% increase in msDA. This suggests that the height contributes the most to increasing or decreasing the daylighting performance of wind towers.

Table 1 Linear regression models output

sDA Linear Regression Models

A	CC	R^2	P-Value	B	CC	R^2	P-Value
Height	-0.827	0.683	1.08E-07	Height	-0.552	0.304	0.003
Length	0.441	0.194	0.021	Length	0.555	0.308	0.003
Orientation	0.009	8.50E-05	0.964	Orientation	-0.065	0.004	0.747

mean lux Linear Regression Models

A	CC	R^2	P-Value	B	CC	R^2	P-Value
Height	-0.828	0.686	0.006	Height	-0.819	0.671	0.007
Length	0.435	0.189	0.242	Length	0.499	0.249	0.171

The output from the linear regression models is shown in Table 1. In the models that consider the msDA as a dependent variable, the height parameter has a correlation coefficient (CC) of −0.827 and −0.552 for placement options A and B respectively. Therefore, the height parameter could be considered to have a strong correlation in models with placement option A, but only a moderate correlation in models with placement option B. The negative value of the CC describes a negative correlation, meaning that an increase in height produces a decrease in the msDA metric. The R square value indicates that the height parameter explains 68.3% of the variance in the msDA in the placement A configurations and 30.4% in the placement B configurations. The P-values for the height parameter are well below the commonly used 0.05 threshold, therefore these correlations are considered statistically significant. The length parameter displays notably lower CC values of 0.441 (placement option A) and 0.555 (placement option B), suggesting that this parameter has a moderate correlation with the msDA metric. These correlations are still statistically significant, with p-values of 0.021 and 0.003, although with a considerable decrease in significance in the case of the configurations with placement option A. The orientation of the models shows very weak and not statistically significant correlations, suggesting that their impact in a dynamic annual daylighting simulation is negligible in the tested positions. Orienting the wind tower opening within the tested range provides similar performance. The regression model using the median lux as the dependent variable shows a similar relationship with the height, with a notable difference in the P-value of the length parameter. In these regression models, the P-value of the length parameters indicates their relationship is not statistically significant.

There is a notable change in the CC and R values between Placement option A and option B in the msDA models. The shallower floor plan arrangement appears to mask the daylight distribution effect of the wind tower in terms of the msDA metric. These arrangements already had msDA levels above 90% in all orientations. The wind towers in the placement B options could only increase the msDA by no more than 5%−10% (depending on the orientation), as opposed to the A placement option, where the wind tower contributed as much as a 43.6% increase in msDA, in the case of the A-8H16L model. Therefore, wind towers do not make a considerable contribution to the msDA levels of the shallower floor plan arrangement. Nevertheless, the mean illuminance results (Fig. 8) show that even in an already well-lit floor plan configuration, the wind tower design parameters have a similar effect to those described for the placement option A configurations (in terms of illuminance levels), given that the shortest and longest wind towers provide the highest mean lux levels.

6 Conclusion

Wind towers are traditional passive cooling strategies used for natural ventilation that can also introduce useful daylighting levels in deep floor plans. The wind tower design parameters have a significant impact on their daylighting performance. The height parameter has the most significant contribution to the daylighting performance of the wind tower. Within the simulated tropical hot and humid climate, shorter and longer wind tower configurations improve the daylighting performance of wind towers. The analysis of the results suggests that studying wind towers in deeper floor plans allows for a better understanding of their contribution to the msDA metric. Analyzing both the msDA and mean illuminance levels in regression models provided a better understanding of the wind tower's daylighting contribution in the deep and shallow floor plan. Wind towers have a more significant daylighting contribution to deeper plan configurations. The findings from this work are limited to the tested conditions. More studies are needed to develop a more comprehensive understanding of wind towers as supplementary daylighting systems by including other parameters such as splayed-well sections, specular materials, multiple apertures, and louvers. Future work will assess the wind tower daylight performance by including additional daylighting metrics such as Annual Sunlight Exposure (ASE), Useful Daylight Illuminance (UDI), Daylight Glare Probability (DGP), and qualitative evaluations using HDR and false-color images. Parametric multi-objective optimization will be done to simultaneously assess the natural ventilation and daylighting performance of the wind tower design.

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