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Effect of Building Orientation on The Cooling Load: The UAE Case Study

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Abstract

UAE's climate is considered one of the hottest and humid regions in the world, making air conditioning systems essential in each house nearly all year long. Air-conditioning systems consume most of the buildings' electricity and that comes at a hefty energy cost. Therefore, any serious improvements in this technology in reducing the needed cooling load will lead to economical gain. Different parameters affect the cooling load of a building including the type of air conditioning system (centralized or decentralized units), the outdoor temperature and humidity, and the orientation of the building. Proper building orientation in Malaysia lead to 7.9% cooling load saving. The aim of this work is to study the effect of building orientation located in UAE on the cooling load. A single room is considered as the baseline building and TRNSYS software is used to calculate its cooling load when oriented to north, west, north–west, and south. The ASHRAE Standard 55 is adopted where the zone temperature ranges between 20°C – 25°C, and the relative humidity between and 40 – 60%. The study concludes that when the room is oriented to north–west the cooling load was at the minimum of 2627 Ton-hr. Whereas the maximum cooling load occurs when the room was oriented to west at 3161 Ton-hr. This led to nearly 17% cooling load saving. Therefore, it is recommended to orient buildings facing the north–west direction in the UAE.

Keywords: *Cooling Load, Building Orientation, Air-Conditioning*

1. Introduction

Air-conditioning (A/C) system is one of the most essential inventions in this century. It is not only helping people survive the heat, but also provides better air quality for the wellbeing [1]. The A/C system efficiency is influenced by many parameters, but headed by the high ambient temperatures. The increase in the outdoor temperature in countries like UAE causes an increase in A/C power consumption and thereby reducing the coefficient of performance (COP) [2]. The UAE is considered one of the most hot and humid countries in the world. Over the past 5 years, Abu Dhabi specifically has 6,726 CDD (cooling degree-day) at 10°C [3]. Referring to the definition of the international climate of ASHREA 90.1–2013, Abu Dhabi falls within the zone number 1A and 1B. Zone 1A is characterized as a very hot and humid, while zone 1B is dry. The thermal criteria to fall under this range is that Abu Dhabi has a CDD 10°C > 5000 [4]. Therefore, improving the A/C systems is important for people living in the UAE. There are many factors affect the efficiency of the A/C system starting with the system type: being centralized or decentralized system. According to Zhou et al. [5], not only the COP of heat pumps in decentralized A/C system is 2.9 while the centralized is 1.7, but also the efficacy of decentralized system is 1.4 while that for centralized systems is 1. This clearly favours the use of the decentralized A/C systems. In addition, the outdoor temperature highly affects the performance of the A/C systems. It was shown when the outdoor temperature increases from 30°C to 36°C, the cooling capacity and the COP decreased by 3.7% and 10.9%, respectively [6]. Furthermore, the orientation of the house is a factor that must be taken into consideration. An experiment under ISO standards 5151 demonstrated the effect of wind in different orientation for the building [7]. Their work shows the outdoor dry bulb temperature of 35°C and the wet bulb temperature of 24°C, whereas it requires an indoor dry bulb and wet bulb temperature of 27°C and 19°C, respectively. Preforming the simulation on different orientation proved that when the house is facing north the performance of the A/C improved. It showed a decrease by 7.9% in cooling capacity while the power consumption increased by 10.2% [7]. Therefore, the energy ratio was dropped by 16.5%. An experiment performed in Malaysia (hot and humid region) studying the effect of building orientation in order to minimize the solar gain and maximise the natural ventilation [8]. Two rooms were considered in the experiment, one was oriented facing the east side and the other was facing the west. The results

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concluded that the east orientation is more sensitive to the solar radiation since the rooms are always hotter than the west side. Focusing on the effect of wall insulation, orientation on the room temperature indicated the total conduction heat gain is minimized at an angle of 200 from the south securing minimum temperature against other orientation [9]. Moreover, using TRNSYS the effect of orientation on the energy saving factor was conducted for 3 cities: Jakarta, Marseille, and Poitiers [10]. The optimal orientation and energy savings were respectively 90° and 5.9% in Jakarta, 270° and 27.4% in Marseille, and 0° and 22.2% in Poitiers. Using Energy Plus simulation program, a study was conducted in Indonesia (tropical climate) to assess the orientation on the cooling load of the building [11]. The results prove that when the building is facing the south the cooling load was the lowest at 7.47 kWh. Another study was done for a four floors office modelled in Bangalore, Chennai, New Delhi, and Ahmedabad [12]. The study concluded that there is no single orientation that yields the best energy efficiency. The mentioned studies proved the effect of orientation on the cooling capacity in different region of the world. The residential building cooling in UAE consumes more than 50% and 36% of the total electricity consumption [13]. Therefore, any serious attempt in reducing cooling load without compromising comfort will translate to huge economical gain and cost saving. It was the objective of this work to consider the UAE climate and demonstrate when a building is properly oriented a great reduction in the cooling load occurs. The TRNSYS software was used in order to simulate the cooling load at different orientation in UAE.

2. Theoretical Formulation

Building orientation can be simply accounted for by changing the solar angles. The solar angles are important parameters as they help in evaluating the amount of radiation directed at a specific location. Therefore, during the simulation when the orientation is changed TRNSYS program re-calculates the solar angles to evaluate the cooling load. There are several angles involved to perform this task. Firstly, the azimuth angle is determined. It is defined as the compass direction from where the sunlight is emitting with 0° and 180° references to the north and south, respectively. In the northern hemisphere, at the solar noon the sun is always directly south. The azimuth angle depends on the latitude and time of the year and is evaluated according to Eq. 1 as:

$$A = Inv.[cos\left(\frac{[Sin(a)*\sin(L)]-\sin(D)}{\cos(a)*\cos(L)}\right)] \quad (1)$$

where a is the altitude angle, L is latitude angle and D is the declination angle. Secondly, the zenith angle is determined. It is the angle between the sun ray and the y-axis [14] and it is complementary with the altitude angle. It is calculated according to Eq.2 as:

$$\theta_z = \text{Inv.}[\cos(\sin(D)\, sin(L) + \cos(D)\ \cos(L)\cos(w))] \quad (2)$$

where, D is the declination angle and it varies from 23.27° on June 21 to -23.27° on December 2022, L is the latitude (at noon $cos(w)$ = 0, and $\theta_z = L - D$), w is the hour angle (at sunrise or sunset, except north and south pole], cos (θ_z) = 0 and $w = \frac{N\,d}{2}$). Thirdly, the hour angle is determined. This is the distance between the meridian line (longitude line) of the house and meridian line of the sun [15]. At noon time the hour angle is equal to nil. But it increases by 15° every 60 minutes when dwelling/house longitude contains the sun. The hour angle varies from negative before the solar noon to positive after the solar noon and is evaluated per Eq. 3 using the standard time (ST) as references:

$$w = (ST - 12) * 15 \quad (3)$$

Fourthly, the declination angle is also determined. It is the angle between the ray of the sun and the equator plane of the earth [16]. The declination angle takes a positive value in the northern hemisphere and a negative value in the southern hemisphere. Meanwhile in the summer-solstice the value of declination angle is 23.5°, while in the winter-solstice is -23.5°. Therefore, the declination angle value ranges as -23.5° < δ < 23.5°. Eq. 4 shows how the declination angle is calculated:

$$\delta = \text{Inv.}[\text{Sin}(\sin(D) = 0.39795\cos[0.98563*(N-173)] \quad (4)$$

where, δ and D are equivalent to the declination angle, N is the number of days starting from January 1. Fifthly, the altitude angle is determined. It is defined as the angle between the rays of the sun and x-axis represented by the ground [16]. It depends mainly on three parameters, i.e., the time of the day, time of the year, and the latitude of the earth. The altitude angle is evaluated according to Eq.5 as:

$$\alpha = Inv.[\sin([\cos(L)*\cos(D)]\ *\cos(w)] + [\sin(L)* \sin(D)])] \quad (5)$$

Sixthly, the angle of incidence (θ_i) of the sun at a tilted surface from the angle from the horizontal (β) is also evaluated. It depends on the declination angle, latitude angle, tilted angle (β), azimuth angle, and hour angle.

$$\theta_i = \sin(\delta)\sin(L)\,cos(\beta) + \sin(\delta)\cos(L)\sin(\beta)\cos(A) + \cos(\delta)\cos(L)\,cos(\beta)\sin(w) - \cos(\delta)\sin(L)\,sin(\beta)\cos(A)\cos(w) - \cos(\delta)\,sin(\beta)\sin(A)\sin(w) \quad (6)$$

After evaluating all the above six angles the Radiant Time Series (RTS) method is used. It is a method provided by ASHRAE (2001) to calculate the cooling load, and it replaced other previous methods like TETD [17]. The RTS method applies the heat balance equation under several simplifications. For example, it does not preform heat balance for the entire internal surfaces, but it assumes that the internal surface and the indoor air have the same temperature. The RTS depends on five main steps shown in Fig.1. First, determining the exterior boundary condition. Second, calculating the heat gains. Third, dividing the heat gains to convective and radiative parts. Fourthly, determining the cooling load for both parts. Fifth and last, summing of the convective and radiative parts.

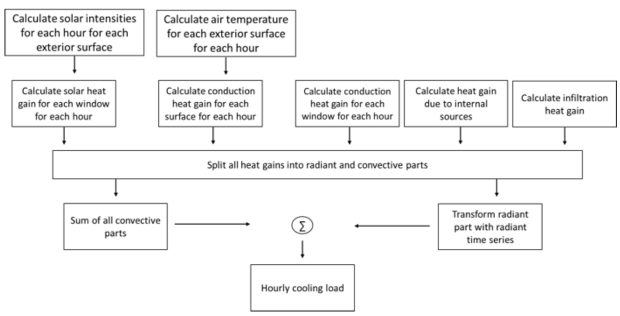

Fig. 1: Summary of the steps used in the RTS method

There are three solar radiation models considered to calculate the cooling load. These are the clear-sky, the isotropic-sky, and the anisotropic-sky models. The clear sky model uses the normal beam evaluation (G_{cnb}) which considers absorption and scattering of solar radiation by the atmosphere in cloudless days [17]. It is formulated according to the following equations:

$$G_{cnb} = G_{on}\tau_b \tag{7}$$

$$G_{on} = G_{sc}\left(1 + 0.033 \cos\left[\frac{360n}{365}\right]\right) \tag{8}$$

$$\tau_b = a_0 + a_1\left[-\frac{k}{\cos(\theta_z)}\right] \tag{9}$$

$$G_{cb} = G_{on}\tau_b \cos(\theta_z) \tag{10}$$

$$\tau_d = \frac{G_d}{G_{cnb}} = 0.271 - 0.294\,\tau_b \tag{11}$$

where the G_{on} is the extra-terrestrial radiation, and τ_b is the atmospheric transmittance that depends on the location altitude and sun's zenith angle. The G_{sc} is the solar constant equivalent to 1266 W/m^2, and n is referred to the number of days. G_{cb} is the clear sky horizontal beam radiation, and τ_d represents the relationship between the beam and diffused radiation.

For the isotropic and anisotropic sky models it is required to calculate the hourly total from the daily total solar radiation using the following equations:

$$r_t = \frac{I}{H} \tag{12}$$

$$r_t = \frac{\pi}{24}(a + b\cos[\omega])\frac{\cos[\omega]-\cos[\omega_s]}{\sin[\omega_s]-\frac{\pi\omega_s}{180}\cos[\omega_s]} \tag{13}$$

$$a = 0.409 + 0.5016\,\sin[\omega_s - 60] \tag{14}$$

$$b = 0.6609 + 0.4767\,\sin[\omega_s - 60] \tag{15}$$

where I is the hourly total radiation [J/m^2], H is the daily total radiation [J/m^2], and ω_s is the sunset hour angle. The isotropic sky model considers the solar radiation diffuse component I_d as isotropic.

$$k_T = \frac{I}{I_0} = \frac{G}{G_0} \tag{16}$$

$$I_0 = \frac{12 \cdot 3600}{\pi} G_{on}\left[\cos(\emptyset)\sin(\delta)(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180}\sin(\varphi)\sin(\delta)\right] \tag{17}$$

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & for\ k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.366k_T^4 & for\ 0.22 \le k_T \le 0.8 \\ 0.165 & for\ k_T > 0.8 \end{cases} \tag{18}$$

$$I_b = I - I_d \tag{19}$$

$$R_b = \frac{\cos(\theta)}{\cos(\theta_z)} \tag{20}$$

$$I_T = I_b R_b + I_d\left(\frac{1+\cos[\beta]}{2}\right) + I\rho_g\left(\left(\frac{1-\cos[\beta]}{2}\right)\right) \tag{21}$$

where k_T is the clearness index, and I_0 extra-terrestrial radiation for a given hour, and ω_2 is the high hour angle while ω_1 is the low hour angle. I_b is the beam component of the solar radiation. I_T is the total radiation summing the beam, isotropic diffused, and reflected components. However, for the anisotropic sky model the diffused component is in the circumsolar direction, near horizon brightness and cloudiness [17].

$$I_T = \left(I_b + I_d\frac{I_b}{I_0}\right)R_b + I_d\left(1-\frac{I_b}{I_0}\right)\left(\frac{1+\cos[\beta]}{2}\right)\left[1+\sqrt{\frac{I_b}{I}}\,sin^3\left[\frac{\beta}{2}\right]\right] + I\rho_g\left[\frac{1-\cos[\beta]}{2}\right] \tag{22}$$

The convective portion is calculated separately and added to the radiative portion to calculate the stipulated cooling load as illustrated in Fig. 1.

3. Geometry Setup

Fig. 2 demonstrates the blueprints of the room considered in the current study. It comprises a length of 2.6 m^2 and a width of 3.1 m^2 and with a total surface area of 8m^2. The figure also shows the location of the door and window as well as the erected 3D model using Google SketchUp. It depicts the projection from the front side (door side) and backside (window side) views. The height of the building is considered 3 m following the common residential building code adopted in the UAE. Table 1 lists the structural elements and their areas, including the door, window, and the building dimensions.

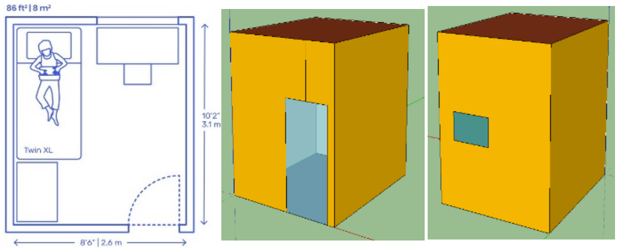

Fig. 2: Blueprints of the room considered in this study and 3D drawing of the room showing the front side and backside using Google SketchUp

Table 1: Building elements and area

Building Elements	Length (m)	Width (m)	Area (m^2)
Whole building	2.6	3.1	8.06
Door	1	2	2
Window	0.85	0.5	0.425

Using TRNSYS 17 program, the study was conducted according to ASHRAE Standard 55 where the air temperature (T_{air}) is set at 23°C and the relative humidity (□) sets at 50%. The comfort requirement of ASHRAE Standard 55 stipulates the zone/room is to be in the temperature and relative humidity range of 20°C – 25°C and 40% – 60%, respectively. The considered building orientations in the simulation are those located north (N), south (S), west (W), and north–west (NW) directions.

Table 2 lists the room wall construction properties in detail. Notice that the ground, the roof, and the walls are made of different construction materials with different thicknesses, thermal conductivities, and the equivalent U values per ASHRAE standards. This baseline room is occupied by single person in adherence to TRNSYS standard occupancy capacity. The natural ventilation applied for each room is equivalent to 1 ACH (air changes per hour) and the leakage type ventilation during occupation period in the simulation is 0.2 ACH according to TRNSYS standards. Furthermore, a mechanical ventilation type is also considered while the lighting heat gains used in the analysis is equivalent to 10 W/m^2.

Table 2: Room walls construction properties

Name	Material	Thickness (mm)	Thermal Conductivity (kJ/h-m-K)	U Value (W/m^2-K)
Ground	Floor	5	0.252	**0.313**
	Stone	60	5	
	Silence	40	0.18	
	Concrete	240	7.56	
	insulation	80	0.144	
Roof	Concrete	15	7.56	**0.233**
	Insulation	50	0.144	
Wall	Brick	240	3.2	**0.339**
	Insulation	100	0.144	
	Plaster	30	5	

4. Results and discussion

Fig. 3 shows the process diagram and corresponding processes involved in TRNSYS simulation studio interface used in the simulation. The weather data is a subset of the obtained UAE metrological data collected during the year in 2021 [18]. The building component is the building envelope inferred from the Google SketchUp that used the outlay wireframe blueprint and 3D geometric model. The Turn and Radiation process blocks shown in the figure are calculator components used to compute different angles like the azimuth and declination for the different building orientations. The lights process block considers the heat gain due to dwelling lightening and it operates as switch according to the occupancy schedule in the simulation. The Cooling block is a calculator command used to measure the cooling load that is required for the dwelling. The Nat. Vent block are divided into two-command modes: The calculator which provides the initial input value given in the simulation and is considered as a fixed value of 1 ACH. The second calculator mode comprises the four switches that each correspond to one of the four considered orientations according to the occupancy schedule. Meanwhile, West, North-West, North, and South are printer commands used to extract the results from TRNSYS simulation and use them in other programs like Excel or MATLAB in order to analyze the results. The Irradiation command is a plotter used to graph the results for radiation calculated in the Turn and Radiation commands. Moreover, the Q Load component shown in the right side is a plotter command that provides a graphical form of the cooling load results for different orientations.

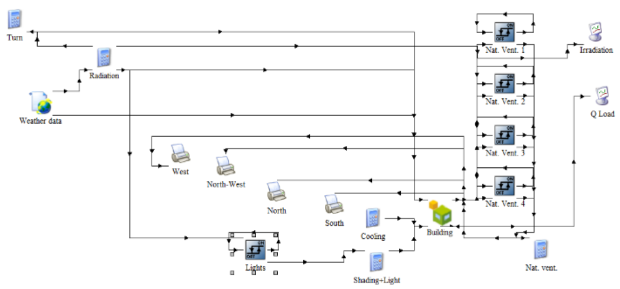

Fig. 3: TRNSYS process simulation studio interface

Fig. 4 shows TRNSYS results for the cooling load during the year for the four different orientations. The abscissa represents the time in hours (8760 hr = 1 year) and the ordinate indicates the cooling load in kJ/hr. The legend in the upper left indicates the cooling load for the four different orientations considered. At the start of the simulation the cooling load is assigned 0 kJ/hr because the presumed and starting conditions are set at 20°C and 50%, that is comfort zone condition assignment. However, as the simulation proceeds, cooling load increases according to the UAE weather data reaching the high outdoor temperature of Abu Dhabi. The overall results are intuitively correct as the cooling load is reaching maximum during the summer season particularly during the hours between 4380 – 5840.

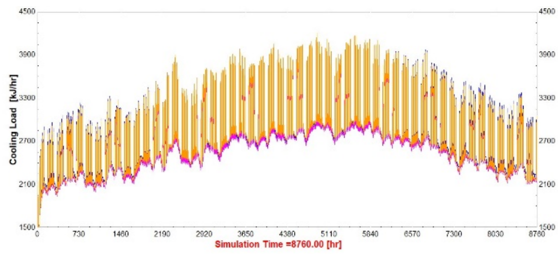

Fig. 4: Cooling load for different orientations

Using the printer commands shown in the TRNSYS process studio interface (Fig. 3), the results shown in Fig. 4 were extracted and imported into excel. Fig. 5 shows the evaluated cooling load data in kW for the hottest day of the year (20 July 2021) for N, NW, W, and S orientations. Additionally, the ambient outdoor temperature is also included during that day which is correlated very well to the cooling load. It is clear that the west orientation requires the maximum cooling load, whereas the north-west required the minimum. However, the results for the north and south orientation overlapped, as they are approximately alike.

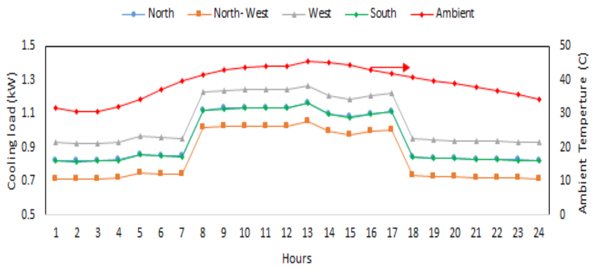

Fig. 5: Cooling load for the hottest day of the year

Table 3 shows the required cooling load for different orientations. The table lists the zone number, the orientations, the area (m^2) and the resulted required power and total load. The results are presented in kW and Tons for the required power, where the total load required in the whole year is in Ton-hr. The results are not the same since the orientation effects the cooling load. The amount of heat gains varies in each orientation since the sun radiation hits the room from different angles causing the cooling load to be affected as a result. The lowest cooling load value is obtained at the north-west orientation and is equivalent to 2627.5 Ton-hr. However, the maximum cooling load of 3161.2 Ton-hr occurs when the room is facing west. Meanwhile, the cooling load for the north and south are nearly at similar values of 2899 and 2895 Ton-hr, respectively.

Table 3: Required cooling load for different orientations

Zone number	Orientation	Area (m^2)	Required power kW (Tons)	Total load required power (Ton-hr)
1	North	8.06	1.16 (0.33)	2899.045
2	North - West	8.06	1.05 (0.29)	2627.458
3	West	8.06	1.27 (0.36)	3161.209
4	South	8.06	1.16 (0.33)	2895.468
Total		-----	4.65 (1.32)	11583.18

5. Conclusion

Several studies proved that changing the orientation of building affects the cooling load of the building. Therefore, choosing the efficient orientation was considered to minimize the amount of energy consumed by the building. Thus, studying the effect of orientation on the cooling load is very attractive. This work studied different orientation for a single room using TRNSYS simulation program subjected to the UAE weather conditions. To start such simulation a blueprint of the room was required to develop the room model using Google SketchUp. Afterwards, TRNSYS3D was used to convert the SketchUp drawing into TRNSYS as building component. In order to complete, the information needed for the simulation, room properties and construction material was applied. The simulation was conducted according to ASHRAE Standard 55 using standard ambient temperate (T_{air} = 23°C) and relative humidity (ϕ = 50%). The results of the simulation indicated that when the room is oriented to the west the cooling load is the highest 3161 Ton-hr. However, when the room is oriented to the north-west the cooling load is equivalent to 2627 Ton-hr. This comprises 16% energy saving in the UAE conditions. As a conclusion, in UAE it is preferred to orient the residential/office buildings to the north-west in order to minimize the consumption of energy.

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