Trends in Applied Sciences Research 4 (3): 167-174, 2009
ISSN 1819-3579

Daylight Availability and Energy Conservation in Industrial Parks of Tehran

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Abstract: This study presents results of a study on estimation of daylight availability on horizontal and south oriented vertical surfaces as well as energy saving in industrial parks of Tehran by daylighting. Beyond our natural affinity for daylight, it is much more effective than electric lighting at entraining the circadian system because the circadian system responds only to high levels of blue light, such as those found in daylight. Horizontal and vertical illuminances were calculated for three established stations by equations of Illuminating Engineering Society of North America. Synchronically illuminances were measured over 15 days between 12 July and 1 August 2007 to confirm calculated data. The correlation of measured and calculated values was reasonable ($r = 0.703$). Regression models were developed between measured and calculated values ($r^2 = 0.8$). Horizontal and vertical illuminances were predicted for 11 industrial parks of Tehran during a working year (294 days) by fitted models. The minimum, maximum, mean and SD of predicted horizontal values found to be of 12.45, 108.12, 66.48 and 24.71 KLx, respectively. Considerable frequency of occurrence of horizontal illuminance in all places (9.7%) was related in values more than 100 KLx. Additionally it was revealed that in 55% of working year daylight could be sufficient for maintaining indoor standard illuminance of 500 Lx. Results of this study suggest high daylight availability and high potentiality of energy conservation in Iran.

Key words: Daylight, horizontal illuminance, energy saving, industrial park

INTRODUCTION

Daylight is the one light source that most closely matches human visual response (Ahmaed, 2002). Daylighting is dynamic in nature, composed of diffuse skylight, reflected light and intense, directional sunlight, all changing in intensity, direction and spectrum as the time and weather change (Leslie, 2003). Beyond our natural affinity for daylight, studies have proven that daylighting has a profound effect on human mood. In the other word, lighting can be used to strengthen the human circadian rhythm, which determines various physiological functions such as sleep, digestion, alertness, depression and probably general health (Hashmi, 2008). Daylight is much more effective than electric lighting at entraining the circadian system; this is because the circadian system responds only to high levels of blue light, such as those found in daylight. Studies have revealed that daylight is three to four times more effective on circadian rhythm than fluorescent lamps and twenty times more effective than incandescent lamps (Hashmi, 2008). Building occupants value the view that windows provide. View gives the occupant visual information about weather, time of day and surrounding activities. Views also can be aesthetically pleasing and give a respite from closely focused study (Leslie, 2003).

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Simulation analyses as well as field-monitoring studies have reported that daylighting controls can result in significant lighting energy savings ranging from 30 to 77% (Ihm *et al*., 2009). Electric energy savings also result in fewer power plant emissions that contribute to acid rain, air pollution and global warming (Leslie, 2003).

At the present time, up to 20% of generated power is consumed for illumination in the country which has main contribution in fuel consumption and air pollution. for instance in 2005, gross power of 178071×10^6 kwh was generated in the country, by consumption of, 32832×10^6 m^3 natural gas, 2612×10^6 L diesel and 6329×10^6 L fuel oil. Consumption of these fuels has resulted in air pollutants as nitrogen oxides, hydrocarbons, sulfur dioxide, carbon dioxide, sulfur tri oxide and carbon mono oxide in large quantities of 147661×10^3, 5302×10^3, 140220×10^3, 95899792×10^3, 2139×10^6 and 198×10^6 kg, respectively (Tavanir Organisation, 2009).

Daylight availability defined in terms of the external skylight illuminance available on an unobstructed horizontal plane for a certain percentage of daytime working hours or for specified periods (Rahim and Mulyadi, 2000). Such data can be obtained either by measurements or by calculations from other meteorological quantities (Alshaibani, 2001).

Since, the launch of International Daylight Measurement Program (IDMP) by the International Commission on Illumination (CIE, Commission Internationale de l'Eclairage) in 1991, measurement of daylight illuminance has been undertaken and reported from various parts of the world (Chirarattananon *et al*., 2007). Since then, however, a few Asian stations have been established in Japan, Hong Kong, Thailand and Singapore, measurement of luminance and illuminance has not yet been undertaken in Iran.

The first step in evaluating the visual performance and energy efficiency provided by daylight requires an accurate estimation of the daylight entering a building (Li *et al*., 2004). This can be performed by experimental equations or computer simulation programs. Daylighting simulations have achieved a high standard of accuracy and realism in the last decade (Lehara and Glicksmanb, 2007) which mostly predict indoor daylight illuminance based on measured weather data.

In respect to no reliable data in Iran upon which to assess the impact of daylight on workplaces adopting a proper method to predict daylight availability could be the viable alternative.

Tehran province is surrounded by 11 industrial parks with maximum distance of 125 km from Tehran. This study was undertaken to estimate outdoor illuminances on both horizontal and vertical surfaces, as well as potentiality of energy saving by daylighting in industrial parks of Tehran Province.

MATERIALS AND METHODS

This study contains two main stages, (1) developing two adequate models for predicting of outdoor horizontal and vertical illuminances in industrial parks of Tehran and (2) estimation of indoor illuminance in an assumed workplace hence predicting of electrical energy conservation by daylighting in this workplace.

Developing Outdoor Illuminance Models

For the purpose of developing adequate models, measurement of global illuminances was conducted on both horizontal and south oriented vertical surfaces by means of special measuring sets in three established stations [Hamadan, Eshtehard (near of Tehran) and Kerman]. Daylight values were monitored over 15 days between 12 July and 1 August 2007 at 1 h intervals from 9 am to 3 pm. Synchronically global horizontal and south facing vertical illuminances were calculated using equations proposed by Illuminating Engineering Society of North America IESNA. In respect to more occurrences of clear skies in measuring period (88%) just data related in clear skies were taken in to account. All of collected data were entered in statistical sheet of SPSS software and adequate regression

Table 1: Properties of industrial parks of Tehran Province

Industrial park	Geographical coordinate	Active units	Current occupants
Eshtehard	N35°42.3′, E50°18.37′	607	12908
Parand	N35°26.97′, E50°59.77′	27	553
Pishva	N35°18.9′, E51°45.07′	0	0
Charmshahr and Salarieh	N35° 12.75′, E51°33.92′	181	2454
Kharazmi	N35°23.42′, E51°53.35′	11	177
Shams-Abad	N35°21.1′, E51°12.15′	754	13622
Abbass-abad	N35°26.58′, E51°50.65′	884	12317
Ali-Abad	N35°21.38′, E51°55.98′	316	3265
Firoozkooh	N35°45.92′, E52°47.42′	17	569
Nassir-Abad	N35°28.38′, E51°4.53′	188	3649
Nazar-Aabad	N35°55′, E50°35′	10	298

models were developed between calculated and measured values of horizontal and vertical illuminances. Details on measuring stations, monitoring periods and adopted equations, could be observed in authors' earlier studies (Shekari *et al*., 2008; Golmohammadi *et al*., 2009). Based on IESNA equations horizontal and vertical illuminances of a working year (294 days) were calculated for 11 industrial parks of Tehran Province from of 8 to 16 h and subsequently were modified with fitted models. Indeed 2646 data for each industrial park and hence 29106 data on horizontal or vertical surface were obtained for all industrial parks. Table 1 shows geographical coordinate and other characteristics of industrial parks. Vertical external illuminance can provide more accurate information than the horizontal one to determine the average indoor illuminance (Li and Lam, 2000). Therefore, in this study, vertical illuminances were applied to predict potentiality of energy conservation and statistical analyses were made on horizontal illuminances solely.

Prediction of Indoor Illuminances and Energy Conservation

The outdoor required vertical illuminance (E_{xv}) for maintaining internal horizontal illuminance of 500 Lx, was estimated using the following equations derived from Lumen method (Rea Marks, 2000).

$$E_{itotal} = \frac{A_w.E_{des}}{A_S} \tag{1}$$

where, E_{itotal} is total interior horizontal illuminance on a reference point from sidelighting in Lx, E_{des} is desired indoor illuminance (500 Lx), A_w and A_s are, the area of the window wall in m² and the area of the window in m², respectively.

$$E_{ig} = E_{xg}.CU_g.\tau \tag{2}$$

where, E_{ig} is interior horizontal illuminance on a reference point from the ground in Lx, E_{xg} is exterior vertical illuminance from the ground on the window in Lx, CU_g and τ are, respectively coefficient of utilization from the ground and net transmittance of the window wall.

$$E_{itotal} = E_i + E_{ig} \tag{3}$$

where, E_i is, interior horizontal illuminance on a reference point from sidelighting in Lx.

$$E_i = E_{xv}.\tau.cu_{sky} \tag{4}$$

where, cu_{sky} and E_{xv} are, respectively coefficient of utilization from the sky and exterior required vertical illuminance on the window to maintain interior desired illuminance in Lx.

Cumulative frequency distribution of outdoor illuminance can indicate the percentage of working year in which a given illuminance is exceeded. Based on this distribution annual electrical energy saving for an assumed workplace was estimated by following equation (Li and Lam, 2000).

$$E_a = \frac{LPD \times A \times H_a \times F}{1000} \tag{5}$$

where, E_a is, annual energy savings in electric lighting (kwh), LPD is, installed lighting power density (w m^{-1}), A and H_a are, respectively the floor area in m^2 and the annual operating hours of the electric lighting system and F is, the fraction of the working year when daylighting can maintain the required indoor design illuminance.

RESULTS

Following regression models were developed to predict horizontal and vertical illuminances in the workplaces:

$$E_{hm} = 0.841E_{hc} + 6.65 \qquad (r^2 = 0.80) \tag{6}$$

where, E_{hm} and E_{hc} are, respectively predicted horizontal illuminance and calculated horizontal illuminance in KLx.

$$Evs_m = 0.906Evs_c + 1.811 \qquad (r^2 = 0.802) \tag{7}$$

where, Evs_m and Evs_c are, respectively predicted South facing vertical illuminance and calculated South facing vertical illuminance in KLx.

The minimum, maximum, mean and standard deviation of total annual data on horizontal plane found to be 12.45, 108.12, 66.48 and 24.71 KLx, respectively. Table 2 shows these values for all industrial parks.

Minimum, maximum and mean hourly values of annual data for all workplaces from 8 to 16 found to be (16.93, 64.92 and 42.28 KLx), (31.76, 82.62 and 59.97 KLx), (44.27, 96.33 and 73.85 KLx), (52.11, 104.95 and 82.53 KLx), (54.01, 108.12 and 85.32 KLx), (49.76, 105.96 and 82 KLx), (40.2, 98.4 and 72.83 KLx), (26.52, 85.65 and 58.6 KLx) and (12.45, 68.61 and 40.96 KLx), respectively. Annual values of four industrial parks at different standard times are shown in Table 3. The maximum and minimum values of mean hourly illuminances were associated with Charmshahr (85.65 KLx) and Eshtehard (39.49 KLx), respectively. Among all indusrial parks as it is shown in Table 4, the maximum

Table 2: Quantities of horizontal illuminances (KLx)

Industrial park	Minimum	Maximum	Mean	SD
Eshtehard	12.45	107.94	66.30	24.78
Parand	13.11	108.04	66.53	24.71
Pishva	13.79	108.07	66.65	24.67
Charmshahr and Salarieh	13.72	108.12	66.73	24.76
Kharazmi	13.85	108.04	66.58	24.67
Shams-Abad	13.35	108.08	66.61	24.69
Abbass-abad	13.78	108.02	66.54	24.69
Ali-Abad	13.91	108.05	66.61	24.67
Firoozkooh	14.33	107.82	66.26	24.74
Nassir-Abad	13.05	107.96	66.37	24.74
Nazar-Aabad	12.52	107.85	66.12	24.80
Total	12.45	108.12	66.48	24.71

Table 3: Annual horizontal illuminance values (KLx) for each standard time/station

Hour/station	Eshtehard	Charmshahr	Shams-Abad	Abbass-Abad
8*	19.38	18.61	18.83	18.13
	64.92	63.22	63.70	62.89
	43.60	42.27	42.65	41.82
9	34.16	33.65	33.80	33.08
	82.66	81.36	81.72	81.02
	61.04	60.08	60.35	59.60
10	46.01	45.95	45.97	45.41
	96.33	95.94	95.73	95.22
	74.52	74.05	74.18	73.62
11	52.98	53.42	53.30	52.96
	104.95	104.62	104.71	104.42
	82.75	82.80	82.79	82.45
12	54.34	55.29	55.03	54.92
	107.94	108.12	108.08	108.02
	85.06	85.65	85.49	85.40
13	49.97	51.36	50.98	51.11
	105.12	105.77	105.60	105.78
	81.29	82.36	82.07	82.23
14	40.30	42.03	41.55	41.09
	96.65	97.71	97.42	97.84
	71.73	73.20	72.80	73.21
15	26.52	28.39	27.87	28.38
	83.10	84.48	84.10	84.74
	57.20	58.95	58.46	59.08
16	12.45	13.72	13.35	13.78
	65.45	67.03	66.60	67.40
	39.49	41.23	40.74	41.46

*Upper, medium and lower rows are related in minimum, maximum and mean values, respectively

Table 4: Frequency percent of various illuminance ranges (KLx) in each station

Range/station	1	2	3	4	5	6	7	8	9	10	11	12
<20	3.8	4.1	3.9	3.8	4.0	3.8	4.0	4.0	4.2	3.9	4.0	3.9
20.01-27.34	3.7	3.3	3.0	3.1	2.9	3.1	2.9	2.9	2.8	3.0	3.6	3.1
27.35-34.69	4.6	5.1	5.3	5.1	5.3	5.3	5.3	5.3	5.6	5.3	4.8	5.2
34.70-42.03	5.7	5.3	4.6	4.7	4.6	5.2	4.8	4.5	4.4	5.4	5.5	5.0
42.04-49.38	7.1	7.3	7.9	7.9	8.0	7.4	7.7	7.9	8.1	7.3	7.2	7.6
49.39-56.72	11.2	11.2	11.0	10.9	11.1	11.0	11.3	11.1	11.4	11.3	11.5	11.2
56.73-64.06	11.7	12.6	12.3	12.5	12.2	12.7	12.1	12.1	11.5	12.5	11.5	12.2
64.07-71.41	9.2	8.2	8.8	8.8	8.8	8.5	8.8	8.9	9.3	8.4	9.2	8.8
71.42-78.75	7.4	7.5	7.6	7.6	7.6	7.5	7.6	7.6	7.7	7.4	7.4	7.6
78.76-86.10	10.0	9.9	9.9	9.8	9.8	10.0	9.7	9.8	9.4	10.0	9.9	9.8
86.11-93.44	6.3	6.5	6.6	6.7	6.7	6.5	6.7	6.6	6.9	6.4	6.3	6.6
93.45-100.78	9.5	9.3	9.3	9.2	9.2	9.4	9.2	9.3	9.0	9.4	9.5	9.3
100.79>	9.7	9.8	9.8	9.9	9.8	9.8	9.8	9.8	9.7	9.7	9.6	9.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100	100.0	100.0	100.0	100.0

1: Eshtehard, 2: Parand, 3: Pishva, 4: Charmshahr, 5: Kharazmi, 6: Shams-Abad, 7: Abbas-Abad, 8: ALi-Abad, 9: Firooz Kooh, 10: Nasir-Abad, 11: Nazar-Abad and 12: Total

frequencies of horizontal illuminances (12%), were related in range of 56.73-64.06 KLx and the minimum frequencies (3%) were in range of 20.0-27.34 KLx. Also, 19% of all frequencies were related in values more than 93 KLx. Mean hourly values of horizontal illuminances in June (with mean monthly illuminance of 91.61 KLx) were considerably higher and in December (with mean monthly illuminance of 38.33 KLx) were less than other months, respectively (Fig. 1). Exterior vertical illuminances of 46.5 Klx was obtained to maintain average internal illuminance of 500 Lx at reference point of 0.5 depth of an assumed workplace in Shams Abad with following properties:

Width of 30 m, depth of 12 m from window wall to the rear wall, height of 4 m, window width of 6 m, window height of 3 m, net transmittance of the window of 0.9, exterior vertical illuminance from the ground on the window of 1 KLx, coefficient of utilization from the sky also from the ground of 0.078.

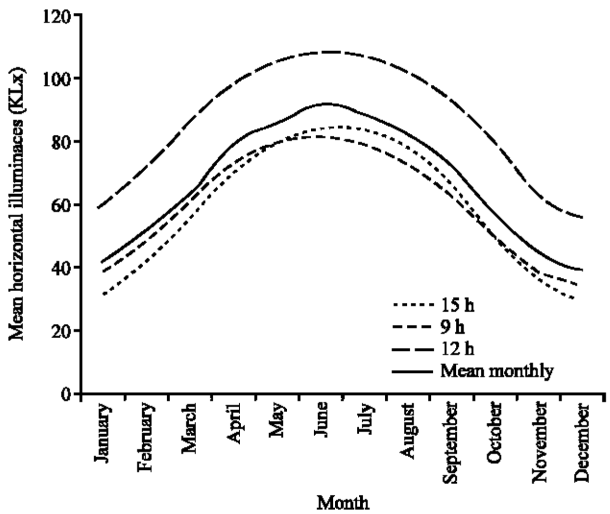

Fig. 1: Mean hourly/monthly horizontal illuminances in Tehran industrial parks

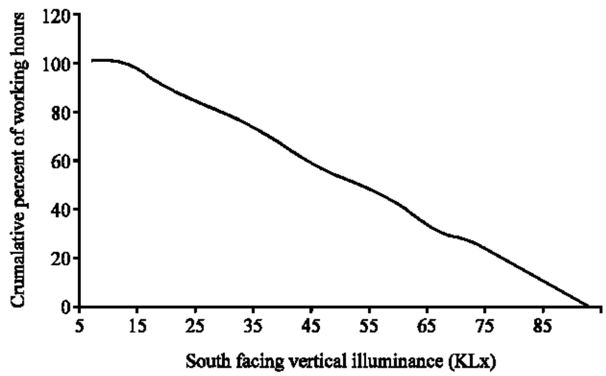

Fig. 2: Cumulative percent of working hours with external south facing vertical illuminance exceeded a given value in industrial parks of Tehran

Regarding to cumulative percents of outdoor vertical illuminaces (Fig. 2), the exterior vertical illuminace of 46.5 KLx will be occurred for more than 55% of working hours in industrial parks of Tehran. It means that for more than 55% of a working year, indoor illuminance of 500 Lx could be maintained by daylight solely.

Based on Eq. 5, for this workplace with installed lighting power density of 9 w m^{-2} and daily operating time of 10 h, the annual energy saving in electric lighting will be 5240 kwh. This amount of energy saving in just one workplace among 2995 active units of Tehran would cause to decrease in annual consumption of 964.16 m^3 natural gas, 73.36 L diesel and 183.4 L fuel oil as well as would result in decrease in annual emission of air pollutants as nitrogen oxides (4.3 kg), hydrocarbons (0.1 kg), sulfur dioxide (4.08 kg), carbon dioxide (2827.18 kg), sulfur tri oxide (52.4 kg) and carbon mono Oxide (5.24). Taking in to account the current cost of 2000 Rials ($0.22) per kwh of generated power, the annual conservation of 10480000 Rials ($1152.8) could be saved due to 5240 kwh annual energy saving.

DISCUSSION

In this study, daylight availability on horizontal and vertical planes as well as energy saving by daylighting were estimated for 11 industrial parks of Tehran Province. The maximum calculated value among 29106 data exceeded 108 KLx which is as high as further expectation for a subtropical region as Iran.

Results of this study exhibited a great variation of illuminances during a working year so that maximum hourly values of annual data were 2 times more than the minimum values in all places also the maximum value of mean hourly illuminances (85.32 KLx) found to be two times more than the minimum corresponding value (40.96 KLx) at all the time. On the other hand horizontal illuminances more than 100 KLx occured more frequently than other places (9.7%) suggesting high daylight values in Tehran industrial parks.

In this study, calculation of vertical illuminances were based on new equations proposed by IESNA (2000), resulted in fitted model different from researchers' prior model (Shekari *et al*., 2008).

Revision of Excel data sheets of illuminances revealed that there are different outdoor horizontal illuminances while occurrences a given outdoor vertical illuminance in different times which verifies the idea of Li and Lam (2000) that vertical external illuminance can provide more accurate information than the horizontal one to determine the average indoor illuminance.

While reearchers agree on the positive impact of daylighting, there is a disagreement in corresponding quantifying energy saving potential. In this study, an annual electrical energy conservation of 55% was estimated for an assumed workplace in Tehran industrial parks whereas daylighting case studies exhibit energy savings of 33 to 60% (Leslie, 2003; Chirarattananon *et al*., 2007; Pattanasethanon *et al*., 2008; Roisin, 2008; Ihm *et al*., 2009). In these studies, differences in calculation methods, building locations and related characteristics have resulted in different findings on energy saving by daylighting.

In conclusion findings exhibited high daylight availability and good potentiality of energy saving in industrial parks of Tehran by daylight so that implementation of daylighting in just one active unit of each industrial park of Tehran, would result in decrease up to 31.826 t in emission of air pollutants and 10608.584 m^3 in fuel consumption which are equal to conservation of 115280000 Rials ($12680.8). For more accurate data long term measurement of illuminances must be made in Iran.

ACKNOWLEDGMENT

This study is based on the first author M.Sc. thesis which was conducted in Hamadan University of Medical Sciences, Iran in 2008.

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