Energy for Sustainable Development 41 (2017) 157–164

Contents lists available at ScienceDirect

Energy for Sustainable Development

Orientation modeling of high-rise buildings for optimizing exposure/transfer of insolation, case study of Sulaimani, Iraq

Shazad Jamal Jalal, Rawand Khasraw Bani *

University of Sulaimani, College of Engineering, Department of Architectural Engineering, Sulaimaniyah, 46001, Iraq

ARTICLE INFO

Article history:
Received 4 February 2017
Revised 7 September 2017
Accepted 8 September 2017
Available online 6 October 2017

Keywords:
Building orientation
High-rise buildings
Insolation exposure
Solar heat transfer
Sustainability
Equity
Sulaimani city

ABSTRACT

This research aims at finding the optimal orientation regarding exposure and transfer of insolation energy in high-rise residential buildings for space conditioning in Sulaimani city, Iraq. A hypothetical high-rise residential building will be studied that has 18 possible orientations and four apartments per floor. Annual Insolation Value (AIV) for each 5° orientation is calculated based on the sun path diagram, linear interpolation and published direct insolation data by NASA. These values were used to calculate AIV for each floor. Different glazing areas, cross section types and glass panes were examined to determine their effect on the fraction of AIV transferred inside the envelope. The results showed that the orientation 70°–160°, 160°–250°, 250°–340° and 70°–340° is the optimal orientation for the four apartments collectively per floor and a whole building. It was also found that the square shaped floor plan of W/L ratio 1:1 has an optimal shape concerning AIV. The common cross section used in the city transferred 20.0% of the AIV inside the building for all orientations. The accumulative annual fraction transferred is negative, which implies excess or shortage of insolation energy based on Heating and Cooling Degree Days. Because of direct proportional relationship, the orientation optimization was not sensitive to variation in both window-wall ratio (WWR) of 20, 25, 30 and 35% and for CMU and brick wall materials. Increasing WWR by 5%, tends to increase the amount of solar heat transfer by 3%. It was found that the heat transfer ratio between conduction through the wall material to radiation through the glazing panes was 1:5.7. The number of glass panes projected the highest effect on the fraction of AIV transferred inside from 20.0% for two panes to 32.5% for one. The results of examining case studies in Sulaimani showed that their orientations deviate notably (except one complex) from the optimal case. Also none of the case studies used the optimal 1:1 ratio which resulted in high increase in the AIV value per each project separately.

Introduction

The number of high-rise buildings is steadily increasing, according to the Council on Tall Buildings and Urban Habitat (CTUH). The increase is substantial in Fareast Asia and Middle East (Council on Tall Buildings and Urban Habitat, 2012). This increase is powered by rapid advances in building and construction technologies, surge of land value in urban areas and population explosion (Kavilkar and Patil, 2014; Gane and Haymaker, 2008). The classification of which type of buildings are qualified as high-rise has many aspects; different institutions have different criteria for a high-rise building to qualify as such. From a structural standpoint, a building is considered high-rise when lateral loadings become a driving structural factor (Khan, 1965). In general a building is considered high-rise if its height is >21 m or above 7 stories (Knoke, 2006). This general criterion is used for distinguishing the case studies of high-rise buildings in the research.

Buildings are responsible for about one-third of total final energy consumption in the world. (International Energy Agency, 2010). Among various building types high-rise buildings consume an enormous amount of energy and resources to build and operate (Lotfabadi, 2015a; Ali and Armstrong, 2006). The energy consumption of high-rise buildings was steadily rising from 1950s to 1970, as Stein (1977) surveyed 86 office building in Manhattan New York city and found that average annual energy use per unit area increased by 206% from 1950s to 1970 (from 406 kWh/m^2 to 840 kWh/m^2). Lam et al., 2004 surveyed the energy consumption of 20 tall office buildings in Hong Kong built between the 1970′s to early 1990′s for 5 years (1996–2000). The annual energy consumption per unit area ranged from 163 to 389 kWh/m^2. The energy breakdown showed that the heating and cooling were the argest components of energy use, 47.5% of total. A major reason for this high share of total energy consumption in heating and cooling results from large areas of exposed façades to direct solar radiation in hot climates that also results in vast energy loss in cold climates. To develop efficient high-rise buildings and mitigate their impact on the environment and resource depletion the sustainable high-rise buildings concept has gained traction. It is partly

* Corresponding author.
E-mail address: rawand.khb@gmail.com (R.K. Bani).

https://doi.org/10.1016/j.esd.2017.09.003
0973-0826/

an attempt at lowering the energy required to operate these types of buildings. A pivotal element in making a high-rise building, or any building for that matter, sustainable is orientation (Li, 2012; Elotefy et al., 2015). Conventionally, the south orientation in the northern hemisphere is preferred for its important properties such as lower solar heat gain in summer, better solar heating in winter and easy daylight control, therefore better daylight compared to the other orientations (Lechner, 2009). Nevertheless any rectangular high-rise building (common and the case in the research) has four orientations, and each two neighbors are opposite (Fig. 1). In addition to the imbalance in insolation (Incident Solar Radiation) exposure between the different orientations, this situation also creates an inequity in apartment value in the same building.

Previous studies

Previous research showed that orientation, among other parameters, is an important factor in devising energy saving strategies for sustainable buildings (Jovanovic et al., 2014). Lotfabadi (2015b) and Raji et al. (2015) analyzed different high-rise building case studies in terms of energy consumption and showed that sustainable strategies pertinent to solar radiation treatment has the greatest effect on saving energy in those buildings. Ling et al. (2007) studied the effect of geometric shape and orientation on insolation energy in high-rise building's façades in the hot and humid climate of Malaysia. They found that the circular shape receives minimum total annual insolation followed by square shape oriented on the cardinal directions. The highest insolation value was on the east, south, west and north orientations respectively. Lau et al. (2016) studied different types of shading devices on different orientations and how they reduce solar heat gain from radiation in the hot and humid climate of Malaysia. They examined twenty models via computer simulations. They determined that 49% of energy consumption in high-rise buildings in their climate is used for cooling loads to offset solar heat gain. They also found that shading devices and high performance glass work best when synchronized with orientation and that the east/west orientation must be shaded due to their high heat gain. Ha (2016) devised an energy efficiency factor for buildings by studying high-rise apartment buildings in Vietnam. It was found that 86% of total heat gain in the buildings studied was from insolation from various orientations, which varies with orientation. Mangkuto et al. (2016) investigated an optimum energy solution based on window to wall ratio, wall reflectance and orientation in a tropical climate. They found that the optimum solution points toward south orientation synchronized with the other variables. The problem of sustainable and equitable exposure of insolation between the four different façades of high-rise residential buildings has not been addressed, which represents a gap in the literature on how to appropriately expose all the façades of the same buildings to insolation. This paper is an investigation into optimizing sustainable and equitable exposure of insolation for four sided residential towers and the effect of window to wall ratio on the amount of insolation transferred inside the buildings. The primary concern in this paper is heating and cooling energy affected by direct insolation and its fraction passing through the building envelope.

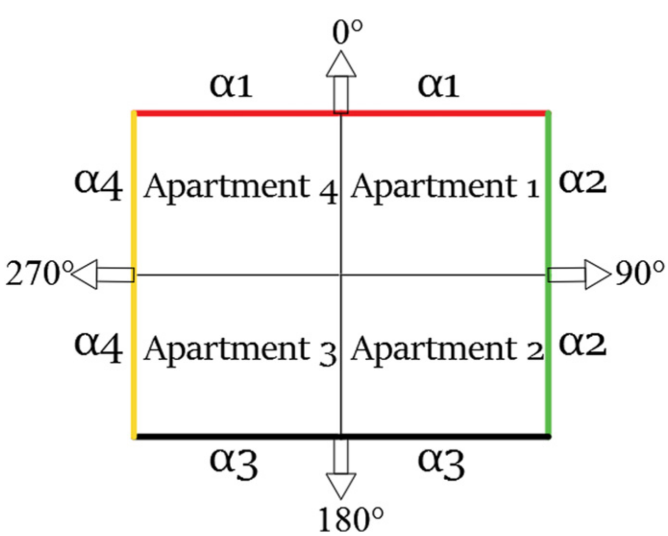

Fig. 1. A typical floor plan in the case of cardinal directions for a high-rise residential building that has four double façades apartments per floor.

Research objective and approach

The aim of the research is to determine the most sustainable exposure and transfer of insolation energy, which means "*minimum Annual Insolation Value (AIV) for the entire high-rise building (four double façades apartments per each typical floor)*" (See section 3.1.4 and The optimal orientation for a high-rise residential building with four double façades apartments per floor section). Also to find the most equitable exposure and transfer of insolation energy which means "*minimum standard error of AIV for the entire building*" (See Fig. 1).

After finding the optimum orientation and geometrical shape, a sensitivity analysis will be conducted to determine the fraction of insolation energy transferred inside for different wall cross sections as well as the common one in the city. Finally, different case studies of high-rise residential buildings will be considered in the city of Sulaimani to compare their orientations, floor plan shapes and solar exposure to the optimal case.

Temperature and insolation in the city of Sulaimani

The city of Sulaimani is in a regions with dry-hot summer and humid-cold winters. It is on latitude 35.5° north and longitude 45.5° east. The city is located 360 km north east of Iraq's capital city Baghdad, and 220 km south east of Erbil, the Iraqi Kurdistan region's capital city (Sulaimani Governorate, 1989). The city experiences a great variation in daily average temperatures throughout a year reaching 60.6 °C between summer and winter. Minimum and maximum daily temperatures reach-10 °C in December and 51.6 °C in July, respectively. The average annual cumulative insolation energy on a vertical surface (building façades) is 1626 kWh/m^2 in the city. The amount varies according to different months, the peak occur in June 207 kWh/m^2 and its lowest in January 65 kWh/m^2 (NASA Atmospheric Science Data Center, 2005). The sunlight hour in the city is maximum in July 14 h and its minimum in December 9 h (Table 1) (Jalal and Bani, 2016).

The insolation energy is an asset (positive) used for solar passive heating in December, January and February, and a liability (negative) in June, July and August as it contributes to heat gain, with different ratios in the remaining months. These positive and negative value ratios were calculated for each month in Sulaimani relying on Heating Degree Days (HDD) and Cooling Degree Days (CDD), based on Point Balanced Temperatures (PBT) of 15 °C for HDD and 20° for CDD (Lechner, 2009). The insolation energy in the city is positive in December, January and February and negative in June, July and August with mixed ratios in the remaining months (Table 1).

Methods

This section describes the calculation methods for first, the value of insolation energy in Sulaimani, and how the data taken from the sun-path diagram of 3ds Max software were used as inputs to formulate linear models to compute the value for each 5° orientations over a year. And secondly, the calculation of the fraction of total insolation energy transferred inside through different assumed cross section materials and types. It is important to notice that the calculations are only for direct insolation from the sun path diagram and cloud cover was not

Table 1
Temperatures, sunlight hours, insolation and Heating/Cooling Degree Days for Sulaimaniyah city.

Months	Average of the daily minimum temperatures °C[a]	Average of the daily maximum temperatures °C[a]	Average monthly sunlight hours (hour/day)[b]	Insolation on vertical surface (1983–2005) kWh/m^2·month[b]	Negative value %CDD of Sum[c]	Positive value %HDD of Sum
January	−1.2	−9.4	9	74.2	0	100
February	−1	12.9	10.5	88.73	0	100
March	2.2	19.6	1	128.6	2	98
April	8	29.4	12.5	146.7	41	59
May	14.1	38.7	13	186.09	91	9
June	19.6	46.8	14	207.36	100	0
July	23.5	51.6	13.5	203.95	100	0
August	21.9	50.2	13	187.77	100	0
September	17.1	43.7	12	152.55	98	2
October	12.2	33.6	11	109.65	72	28
November	5.4	20.3	10	76.68	7	93
December	0.6	11.3	9	65.01	0	100

[a] Researchers via (NASA Surface Meteorology and Solar Energy, 2005). (Average for 1983–2005).
[b] Jalal and Bani, 2016.
[c] Calculated from (Weather Underground, BiZee Degree days 2014) average of three years was taken for Sulaimani [18].

included. That subject will be in the scope of a future research where it will be modeled with the orientations.

Annual insolation value (AIV) on vertical surfaces (building façades) depending on orientations in Sulaimani

The procedure of calculating the annual insolation value AIV for each 5° orientation can be summarized in the following steps:

1- The sunlight hours were estimated for the eight main orientations namely north, northeast, east, south east, south, southwest, west and north west of azimuths: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° from the sun path diagram of 3dsMax software and using Sulaimani's geographical location (Table 2).
2- The sunlight hours for each 5° interval between any two adjacent main orientation were calculated using linear interpolation by the following equation (Tables 3a–3h Appendix):

$$h = \Delta H.5^{\circ}/45^{\circ}\ldots \quad (1)$$

where: h = number of sunlight hours for the interval orientation and ΔH = difference in sunlight hours for the main orientation.
3- The cumulative insolation energy was calculated for every 5° for each month by multiplying the sunlight hour for the specific orientation by the value of insolation for the month in kWh/m^2 (Tables 4a–4h Appendix).
4- The AIV was calculated for each 5° orientation by multiplying the amount of cumulative insolation energy for each month by the ratios of HDD and CDD of that month then summing the values of the twelve month according to the following equation (Table 5):

$$\begin{aligned} AIV = {} & X1 + X2 + X3(0.98-0.02) + X4(0.59-0.41) \\ & + X5(0.09-0.91) - X6 - X7 - X8 + X9(0.02-0.98) \\ & + X10(0.28-0.72) + X11(0.93-0.07) + X12\ldots \end{aligned} \quad (2)$$

where:
$X = 1, 2, 3\ldots 12$ is the cumulative insolation energy for the month for any orientation. The numbering index refers to the month i.e., 1 = January, 5 = May and so on. The plus and minus signs refer to whether the insolation is desired or not. They are based on the percentage of HDD and CDD in each month.

The calculation of AIV differs from the preceding research (Jalal and Bani, 2016), in the way the sunlight hours were estimated for each 5°. This research relied on linear interpolation method to estimate the sunlight hours for each 5° interval, which gave better results than linear regression models that was used in the previous research. The current method yielded more accurate results compared to the previous one in calculating the sunlight hours taken from the sun path diagram for (95°, 100°, 105°, 270°, 275°, 280°, 285° and 315°) orientations. The average algebraic percentage error for the current method is 0.31%, while it was 2% for the previous method compared to values taken from the sun path diagram for the 5° intervals. The relative error, which is equal to the percentage ratio between the difference of estimated and actual values from the sun-path diagram to the actual values themselves, was calculated for both methods. The average relative error was 0.3% and 2% for the current and previous method, respectively (Table 6). Therefore the current method is more suitable and accurate to use for estimating sunlight hours for 5° interval orientations.

Table 2
Monthly sunlight hours of direct insolation exposure of the main eight orientations for vertical surfaces in Sulaimani[a].

Sunlight hours of direct insolation exposure for vertical surfaces in Sulaimani hour/day[b]	January	February	March	April	May	June	July	August	September	October	November	December
North 0°	0	0	0	1.75	4.25	7	6.25	4	1	0	0	0
North East 45°	1.5	2.75	3.25	5	5	6.75	6.75	5.25	4.25	3	2.25	1
East 90°	4.75	5.5	6	6.5	6	7.25	6.5	6.5	6	5	5	4
South East 135°	8	7.75	8	7.25	7.75	8	7.25	7.75	7.75	7.5	8	7.75
South 180°	9	10.5	11	10.75	8.75	7	7.25	9	11	11	10	9
South West 225°	7.5	7.75	7.75	7.5	8	7.25	6.75	7.75	7.75	8	7.75	8
West 270°	4.25	5	5	6	7	6.75	6.5	6.5	6	6	5	5
North West 315°	1	2.75	3	5.25	5.25	6	5.25	5.25	4.25	3.5	2	1.25

[a] Jalal and Bani, 2016.
[b] Each value in the table represents the average of the 1st and the 15th of each month.

Table 5
Annual Insolation Value (AIV) for vertical surfaces, calculated for every 5° in Sulaimania[a].

Orientations (in degrees)	AIV	Orientations (in degrees)	AIV	Orientations (in degrees)	AIV	Orientations (in degrees)	AIV	Orientations (in degrees)	AIV	Orientations (in degrees)	AIV	Orientations (in degrees)	AIV
0	−314	55	−287	110	−220	165	−198	220	−201	275	−257	330	−287.1
5	−310	60	−278	115	−230	170	−195	225	−206	280	−261	335	−293.6
10	−314	65	−272	120	−223	175	−190	230	−209	285	−264	340	−295.3
15	−312	70	−262	125	−215	180	−189	235	−220	290	−271	345	−301.8
20	−305	75	−256	130	−215	185	−190	240	−224	295	−265	350	−304.4
25	−304	80	−247	135	−214	190	−191	245	−230	300	−269	355	−313.7
30	−297	85	−240	140	−213	195	−191	250	−230	305	−273	360	−314.3
35	−299	90	−237	145	−207	200	−198	255	−237	310	−277		
40	−296	95	−235	150	−205	205	−197	260	−244	315	−275		
45	−297	100	−235	155	−202	210	−204	265	−251	320	−275		
50	−294	105	−228	160	−200	215	−204	270	−259	325	−284		

[a] Researchers, based on Table 1 and Tables 4a–4h.

AIV on apartments' façades depending on orientation in Sulaimani

The research considers a hypothetical high-rise residential building with a rectangular floor plan with variable side lengths or width/length (W/L ratio) varies from 1:1 to 1:n (n > 1). The floor plan is typical for the entire building and it consists of four equal sized apartments. Each apartment receives solar radiation through two elevations normal to each other (Fig. 1). There are 18 possible combinations of orientations for the four apartments in the typical floor plan considering 5° intervals. For example: the possible orientations for the case of cardinal directions would be as the following rotating clockwise: the first apartment (0°–90°), the second (90°–180°), the third (180°–270°) and the fourth one (270°–0°) (Fig. 1).

The sign for the AIVs on all the elevation façades is minus indicating a deficit (Table 5), meaning it is either excessive hence contributes to heat gain or insufficient for solar heating. The AIV for any double façades apartment can be determined by algebraically summing the AIV for both its orientations, and then the resulting AIV will also have a minus sign (Table 7).

Wall cross-section and glazing area

The façades are exposed to insulation, however the energy that actually effects the inside space is based on the wall cross section and glazing type and area. The amount of solar energy fraction (AIV fraction) transferred inside the buildings depends on the relationships in Eqs. (3)–(5) (Cengel and Ghajar, 2015).

$$Q_{Total} = Q_C + Q_R \ldots \quad (3)$$

Table 6
Comparison of relative error between regression and interpolation methods.

Orientation (in degrees)	AIV by regression method[a]	AIV by interpolation method[b]	Actual AIV[a]	% Error of regression (column 2–column 4) × 100/column 4	% Error of interpolation (column 3–column 4) × 100/column 4
95	−233.9	235.3	246	−5.2	−4.3
100	−266.6	235.2	241.4	8.6	−2.6
105	−239.6	227.7	236	−0.8	−3.5
110	−260.9	220.5	246.3	7.2	−10.5
275	−271.2	256.6	243.8	13	5.3
280	−249.1	260.5	242.1	−0.7	7.6
285	−242.4	264.3	250.9	−1.6	5.3
290	−246.9	271.5	258	−4.5	5.2
Average	NA	NA	NA	2	0.3

[a] Jalal and Bani, 2016 [16].
[b] Researchers, calculated based on Table 5.

$$Q_C = [(1\text{–}WWR)\ U_{Wall} + WWR\ U_{Glass}].\alpha\ q/ho.1000/730\ldots \quad (4)$$

$$Q_R = WWR.SHGC.SC.q.1000/730\ldots \quad (5)$$

where*:

Q_{Total} the total of AIV transferred inside the building in kWh/m^2/month.
Q_C the amount of conductive heat transfer due to the effect of -direct insolation through both the walls and the windows.
Q_R the amount of direct radiation heat gain through the window area.
U_{Wall} is the coefficient of thermal transmittance of the assumed wall cross-section (Baseline = 0.58 W/m^2·K°) and (Brick core 0.56 W/m^2·K°).
U_{Glass} is the coefficient of thermal transmittance of the assumed window (Double pane = 1.81 W/m^2·K°) and (Single pane = 5.9 W/m^2·K°).
α solar absorptivity of the exterior paint (0.57) average of 0.73 and 0.4 for half-light and half-dark paints, respectively.
q is the monthly cumulative direct insolation on vertical façade in any orientation in kWh/m^2/month (Tables 4a–4h).
h_o is the outside heat transfer coefficients for combined conduction/convection and radiation, for summer (22.7 W/m^2·K°) and for winter (34 W/m^2·K°).
WWR window to wall ratio which is the glazing area fraction of the total wall area.
1000/730 conversion from kWh/m^2/month to W/m^2 (one year taken as 8760 h).
$SHGC$ solar heat gain coefficient of the glazing (0.7) for clear double glazing and (0.86) for single clear glazing.
SC shading coefficient of the glazing (0.8) for clear double glazing and (1) for single clear glazing.

To calculate the amount of AIV transferred inside the building a wall cross-section was assumed based on the most common practice in Sulaimaniyah, the glazing type was assumed as a double clear glazing with air gap also for the same reason (See Fig. 2). For the sake of comparison the effect of window sill and frame was not included. The glazing area was set as a variable to detect the relationship between its ratio (WWR) and the fraction of the AIV transferred inside. As in the case of calculating the AIV itself, the amount of AIV transferred inside was also summed based on factoring by HDD and CDD, therefore Eq. (2) was also used to sum the fraction of AIV transferred inside. For sensitivity analysis: Four WWR cases were tested, a baseline of 30% which corresponds to common practice in Sulaimaniyah city, then

Table 7
Annual Insolation Value (AIV) for single double façade apartments per floor in Sulaimani[a].

Orientations of apartment 1 (in degrees)	AIV1[b] kWh/m^2	Orientations of apartment 2 (in degrees)	AIV2[b] kWh/m^2	Orientations of apartment 3 (in degrees)	AIV3[b] kWh/m^2	Orientations of apartment 4 (in degrees)	AIV4[b] kWh/m^2
0–90	−551	90–180	−426	180–270	−448	270–0	−573
5–95	−545	95 - 185	−426	185–275	−447	275–5	−567
10–100	−549	100–190	−427	190–280	−452	280–10	−574
15–105	−540	105–195	−419	195–285	−455	285–15	−576
20–110	−526	110–200	−419	200–290	−470	290–20	−577
25–115	−534	115–205	−427	205–295	−462	295–25	−569
30–120	−520	120–210	−427	210–300	−473	300–30	−566
35–125	−515	125–215	−419	215–305	−477	305–35	−572
40–130	−511	130–220	−416	220–310	−478	310–40	−573
45–135	−511	135–225	−420	225–315	−481	315–45	−572
50–140	−507	140–230	−422	230–320	−485	320–50	−569
55–145	−494	145–235	−427	235–325	−504	325–55	−571
60–150	−482	150–240	−428	240–330	−511	330–60	−565
65–155	−474	155–245	−432	245–335	−523	335–65	−565
70–160	−463	160–250	−430	250–340	−525	340–70	−558
75–165	−454	165–255	−435	255–345	−539	345–75	−558
80–170	−442	170–260	−439	260–350	−549	350–80	−552
85–175	−430	175–265	−441	265–355	−565	355–85	−554

[a] Reseachers, based on Table 6.
[b] AIV of single double façade apartment = AIV of first orientation + AIV of adjacent orientation.

20%, 25% and 35% to examine the relationship between WWR and the fraction of AIV passing through the envelope. Three cross section were also examined, the base line with CMU block in the core and double pane glass (Fig. 2), a second case with fired brick in the core with double pane glass and a third case with single pane glass and CMU in the core.

Results and discussion

In this section we will indicate the optimal and least optimal orientations for a single double façade apartment, a floor of four double façade apartments and the optimal ratio for such a floor in a high-rise residential building.

The optimal sustainable and equitable orientation for a double façade apartment

The average AIV on both façades of a single apartment in all 72 cases (18 possible cases if a floor is considered) is −497 kWh/m^2 with a standard deviation of ±57 kWh/m^2. The optimal orientation (least total AIV of two adjacent orientations) for a single apartment in any floor of the building is 130°-220° with an AIV of −416 kWh/m^2. The worst orientation is 20°–290° with an AIV of −577 kWh/m^2, considering that the "minus sign" is a reference to a deficit in insolation energy (Table 7). This means that the optimal orientation has a 1.39 times advantage for each square meter façade over the worst orientation. If we consider a façade of 60 m^2 area for an apartment (a common practice in Sulaimani) the difference between the two orientations in AIVs is 9660 kWh ([577 × 60]-[416 × 60] = 9660).

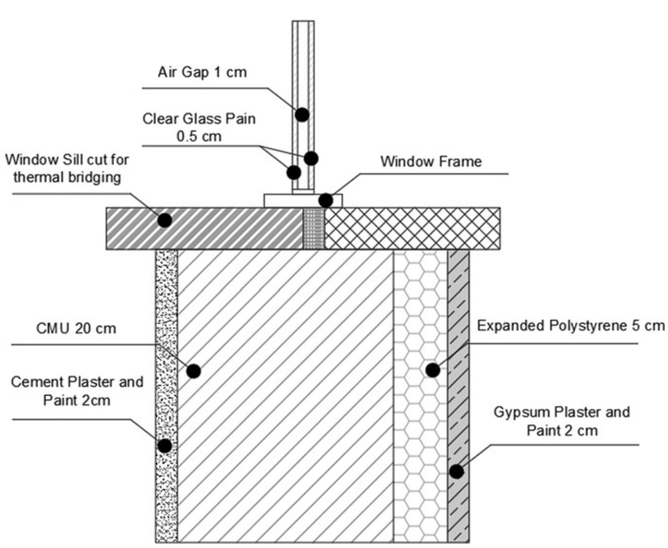

Fig. 2. Wall cross section and glazing specifications.

The optimal orientation for a high-rise residential building with four double façades apartments per floor

There are 18 possible cases if all four apartments considered in the typical floor. The total AIVs on the façade of a single floor (four apartments) is −1988 kWh/m^2 with a standard deviation of ±7 kWh/m^2 (Table 8). This means a relatively close AIV for the 18 different orientations cases per square meter because of the small value of the standard deviation.

If the average area of the eight different façades for all four double orientation apartments in a single floor is considered, then the total AIV for a single floor will equal −477,051 kWh. This is based on an average 60 m^2 façade (common in Sulaimani) and calculated as [60 × 4 × total AIV for the 8 orientation per floor], with a standard deviation of ±1642 kWh (Table 8).

The most sustainable orientation (*least total AIVs of two adjacent orientations for the four apartments*) of a building with the highest equity (*minimum difference of the total AIVs of two adjacent orientations between four apartments per floor*) taking into account all its four double orientation apartments in a single floor is 70°–160°, 160°–250°, 250°–340° and 70°–340° (Fig. 3A). The total AIV for the optimal orientation is −1975 kWh/m^2 with a standard deviation of ±58 kWh/m^2 and 474,000 kWh for the total area of the eight orientations (four apartments) in the floor. This orientation has the least deficit in insolation energy per square meter in a single floor compared to the other possible orientations with a relatively low variations as evidenced by the standard deviations. Although the most equitable case is 60°–150°, 150°–240°, 240°–330° and 60°–330° because it recorded the minimum standard deviation of ±57 kWh/m^2, this case is not the most sustainable because of its high deficit of insolation of −1986 kWh/m^2. The second most sustainable orientation case is 40°–130°, 130°–220°, 220°–310° and 40°–310°. The total AIV for this orientation is −1979 kWh/m^2 with a standard deviation of ±57 kWh/m^2 and 474,000 kWh for the entire façades area of the floor. The least sustainable orientation among the 18 cases is 10°–100°, 100°–190°, 190°–180° and 10°–280° (Fig. 3B). The total AIV for this orientation

Table 8
Annual Insolation Value (AIV) for four double façade apartments per floor in Sulaimani.

Orientations of apartment 1, 2, 3 and 4 in a floor (in degrees)	Total AIV[a] kWh/m^2	Standard deviation[b] ± kWh/m^2	Orientations of apartment 1, 2, 3 and 4 in a floor (in degrees)	Total AIV[a] kWh/m^2	Standard deviation[b] ± kWh/m^2
0–90, 90–180, 180–270, 270–0	−1998	64	45–135, 135–225, 225–315, 315–45	−1983	55
5–95, 95–185, 185–275, 275–5	−1985	61	50–140, 140–230, 230–320, 320–50	−1983	52
10–100, 100–190, 190–280, 280–370	−2001	62	55–145, 145–235, 235–325, 325–55	−1996	51
15–105, 105–195, 195–285, 285–375	−1990	63	60–150, 150–240, 240–330, 330–60	−1986	49
20–110, 110–200, 200–290, 290–20	−1990	59	65–155, 155–245, 245–335, 335–65	−1994	50
25–115, 115–205, 205–295, 295–25	−1992	56	70–160, 160–250, 250–340, 340–70	−1975	50
30–120, 120–210, 210–300, 300–30	−1986	52	75–165, 165–255, 255–345, 345–75	−1986	53
35–125, 125–215, 215–305, 305–35	−1983	56	80–170, 170–260, 260–350, 350–80	−1982	55
40–130, 130–220, 220–310, 310–40	−1979	57	85–175, 175–265, 265–355, 355–85	−1989	62

[a] Researchers, based on Table 7, where total AIV = AIV1 + AIV2 + AIV3 + AIV4.
[b] Researchers, based on Table 7, the standard deviation for four AIVs of single apartment per floor.

is −2001 kWh/m^2 with a standard deviation of ±62 kWh/m^2 and −480,240 kWh for the entire façade area of the floor (Table 8). Therefore the difference between the most and least sustainable high-rise building orientation is −6240 kWh.

The optimal W/L ratio of rectangular floor plan

After determining the optimal orientation for a high-rise residential building, the next step is to find the best (W/L) ratio of rectangular floor plan based on the amount of AIV received by its apartment's façades. The rectangular shape does not necessarily mean straight clean sides; protrusions also can be accounted for by combining their added area to the façades' area to make a geometric comparison.

The numbers and calculations demonstrated in (Table 8) are for a square, i.e. a rectangle with (W/L) ratio of 1:1. Changing the W/L ratio will also change the AIV for the orientations. For example in the case when the apartments are on the four cardinal orientations 0°–90°, 90°–180°, 108°–270° and 270°–0° when the W/L ratio changes from 1:1 to 1:1.5, 1:2, 1:2.5 and 1:3 the AIV increases for a floor from −1988 kWh/m^2 to −2501 kWh/m^2, −3005 kWh/m^2, −3508 kWh/m^2 and −4011 kWh/m^2, respectively. This means when the W/L ratio changes from 1:1 to 1:1.5, 1:2, 1:2.5 and 1:3 the deficit insolation energy changes increase to 1.25, 1.5, 1.75 and 2 times respectively. Whereas when the L/W ratio also changes in the same ratios, the AIV variations of 2612 kWh/m^2, −2988 kWh/m^2, −3485 kWh/m^2 and −3981 kWh/m^2 will be approximately the same and the percentage errors do not exceed ±4%.

Solar heat transfer through the wall cross-section materials for high-rise residential buildings and sensitivity analysis

The results showed that an average of 20.0 ± 0.5% of the AIV is transferred inside through conduction and radiation for the baseline cross section. About 85.0% of this transfer occurred by radiation through the windows, the ratio between conduction and radiation heat transfer inside (*QC: QR*) is 1:5.7 for 30% of WWR (common practice). When the WWR changed from 30% to 20%, 25% and 35% the conductive heat transfer (QC) changed from 15.0% to 18.7%, 16.5% and 13.8%, respectively. The relationship between the fraction of AIV transferred and amount of WWR and the ratio (QC + QR) is proportional. When the WWR changes by ±5%, the ratio of QR/QC changes by ±3% (Table 9). The amount of AIV was factored by the cross section to 20.0 ± 0.5% (transferred inside) in all directions. The "minus sign" indicates a deficit or excess in AIV received or needed based on the CDD and HDD for heating or cooling. Changing the WWR from 30% to 20%, 25% and 35% changed the fraction of AIV transferred inside from 20.0% to 13.9%, 16.9% and 23.0% respectively (Table 9). Changing the core of the cross section from CMU to fired brick had minimal effect as QC decreased by an average of −10.13 W/m^2 to −10.08 W/m^2 (Table 9).

However, changing the window from double pane to single pane QC changed substantially from −10.13 to −23.08 (2.3 times). Also QR changed substantially from −57.54 to −86.85 (1.5 times). The fraction of AIV transferred inside changed from 20.0% to 32.5% (1.6 times). The ratio QC:QR changed from 1:5.7 for double pane window to 1:3.8 for single pane window (Table 9).

Case studies in Sulaimani

The number of high-rise residential buildings in Sulaimani city increased rapidly in the span of the last ten years after the economic boom of 2003 in Iraq. Three projects were chosen for examination, the first is the Jaff towers which is composed of two residential towers each of 31 floors (the highest residential towers in Iraq). The second project is Danya complex, which consists of 6 residential towers each of 30 floors. The third project is Goizha complex that is composed of 11 towers each of 13 floors. All projects have four apartments per floor except Jaff towers have six apartments per floor. For the case of

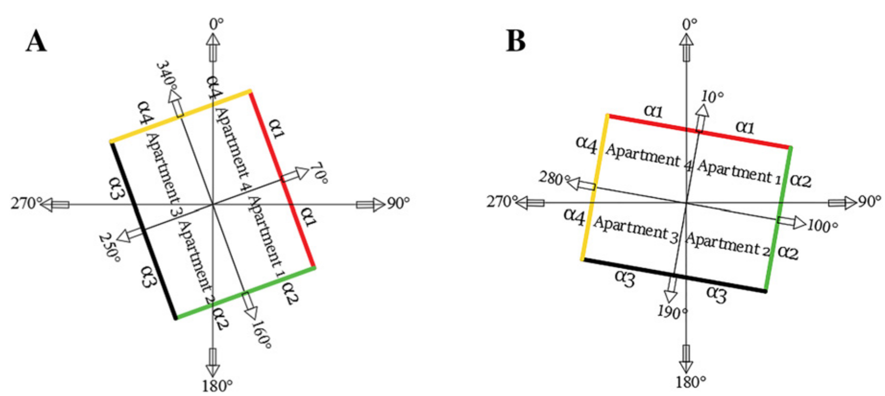

Fig. 3. A – The most sustainable and equitable orientation in Sulaimani city. B – The least sustainable and equitable orientation in Sulaimani city.

Table 9
Average solar heat transfer for different wall cross-sections.

Cross section	WWR %	QC W/m^2	QR W/m^2	QC + QR W/m^2	(QC + QR) × 100/AIV %	STDV ± W/m^2	QC/QR 1: n	QC %
CMU + DPG	20	−8.82	−38.36	−47.18	13.9	0.4	4.3	18.7
	25	−9.47	−47.95	−57.42	16.9	0.4	5.1	16.5
	30[a]	−10.13	−57.54	−67.67	20.0	0.5	5.7	15.0
	35	−10.78	−67.13	−77.91	23.0	0.5	6.2	13.8
Brick + DPG	30	−10.08	−57.54	−67.62	19.9	0.5	5.7	14.9
CMU + SPG	30	−23.08	−86.85	−109.92	32.5	1.1	3.8	21.0

Source: Researchers based on Eqs. (3), (4) and (5).
CMU (concrete masonary unit), DPG (Double Pane Glass), SPG (Single Pane Glass) and STD (Standard Deviation of Population).
[a] Common cross-section in Sulaimani.

Jaff tower four corner apartments were assessed because each of the remaining two apartments has one façade and do not match with the assumed hypothetical case of the research. Concerning the Danya project is divided into two groups because of different orientation for each group. The objective of analyzing these projects is to evaluate the orientation and floor plans' geometric shapes of the towers, then compare them with the results obtained in the research in terms of AIV.

Orientation evaluation of case studies

The orientation of Jaff towers is found to be 0°–90°, 90°–180°, 180°–270°, 270°–0° (AIV = −1998 kWh/m^2/floor), Danya complex has two types of orientations the first 3 towers are on 83°–173°, 173°–263°, 263°–353°, 353°–83° (AIV = −1995 kWh/m^2/floor) and the second 3 are on 73°–163°, 163°–253°, 253°–343°, 343°–73° (AIV = −1976 kWh/m^2/floor), and the Goizha complex is on the 66°–156°, 156°–256°, 256°–343°, 343°–66° orientation (AIV = −1988 kWh/m^2/floor). The case studies substantially deviated from the optimal orientation of 70°–160°, 160°–250°, 250°–340° and 70°–340° (AIV = −1975 kWh/m^2/floor), except the second group of Danya complex (Table 10).

Shape evaluation of case studies

The W/L ratios for both apartment types per floor of Jaff towers is 1: 1.52 and 1.14: 1.89, Danya complex 1: 1.83 and 1.27: 2.14 and for Goizha complex is 1: 1.22 and 1.04: 1.21. None of the case studies are of the optimal ratio of 1:1. This deviation from the optimal shape drastically increases the insolation deficit (higher AIV) when taking the whole project into account, meaning factoring in the façade area of all the floors and all the towers collectively. The average increasing rate depending on the above W/L ratios is 1.6 times for Jaff towers, 1.9 times for both types of Danya complex and 1.22 times of Goizha complex. This extent of the effect of the W/L ratio for all the façades of the entire projects can be easily noted in the second group of Danya towers, despite it been the closest to the optimal orientation, it is insolation deficit difference from the optimal shape and orientation together is −21,362 MWh annually. The Goizha complex however has the lowest deficit (lowest AIV), its difference from the optimal orientation and shape is −8634 MWh annually.

The highest insolation deficit (highest AIV) is of the first group of Danya complex, it is difference from the optimal shape and orientation is −21,978 MWh annually. As a result, the increasing rate from the optimal case for Jaff towers, Danya complex and Goizha complex are 1.40, 1.51, and 1.13 times, respectively (Table 11).

Conclusions

1- Estimating sunlight hours for every 5° orientation by linear interpolation method is more accurate than linear regression method.
2- The optimal most sustainable orientation for a double façades residential apartment in a high-rise building is Sulaimani is 130°–220°, and the least sustainable orientation is 20°–290°. The optimal orientation has an advantage of 161 kWh/m^2 in insolation deficit over the least sustainable orientation.
3- The most sustainable and equitable orientation for a floor plan in a high-rise residential building in Sulaimani is 70°–160°, 160°–250°, 250°–340° and 340°–70°. The least sustainable and equitable orientation is 10°–100°, 100°–190°, 190°–280° and 280°–10°. The first orientation has an advantage of 6240 kWh in insolation deficit annually.
4- The optimal shape for a floor plan of a high-rise residential building is a square W/L of 1:1, when this ratio increases the insolation deficit also increases. For example the W/L ratios of 1:1.15, 1:2, 1:1.25 and 1:3 the insolation deficit increases by 1.25, 1.5, 1.75 and 2 times compared to the square shape.
5- Using the square shape to achieve highest sustainability and equitability in a high-rise residential does not necessarily mean using a straight line square i.e., a clean box. The floor plan can rather host numerous protrusions or recessions as long as the total length of its sides' maintains the ratio of 1:1.
6- AIV evaluation of orientation and shape of different case studies in Sulaimani showed that the projects do not conform to the optimal orientation and shape except the second group of Danya complex that has a close orientation to the optimal orientation but no adherence to the optimal shape.
7- This unconformity to the optimal orientation and shape in Sulaimani, substantially increased the insolation deficit (high AIV) per project, ranging from 1.13 to 1.52 times the optimal case reaching −21,987 MWh annually in the worst case.
8- The total fraction of AIV that transfers through the envelopes is 20.0% in all directions and windows accounted for >85.0% of this transfer. Also the transfer is negative when accumulated annually which is a sign of deficit or excess of solar energy.

Table 10
Orientations, W/L ratios and AIVs per floor of various high rise residential buildings in Sulaimani[a].

Project name	No. of towers	No. of floors	Orientations of apartment 1, 2, 3 and 4 in a floor (in degrees)	W/L ratio[b]	AIV[c] of 1:1 ratio kWh/m^2/floor
Jaff Towers	2	31	0–90, 90–180, 180–270, 270–0	1: 1.52 and 1.14: 1.89	−1.998
Danya Complex1	3	30	83–173, 173–263, 263–353, 353–83	1: 1.83 and 1.27: 2.14	−1.995
Danya Complex2	3	30	73–163, 163–253, 253–343, 343–73	1: 1.83 and 1.27: 2.14	−1.976
Goizha Complex	11	13	66–156, 156–246, 246–336, 336–66	1: 1.22 and 1.04: 1.21	−1.988

[a] Researchers, based on drawings of the specific projects.
[b] Researchers, the dimensions of each apartment is divided by the smallest dimension.
[c] Researchers, estimated by interpolation depending on Tables 3a–3h and 4a–4h.

Table 11
Comparison of AIVs between optimal and real case studies in Sulaimani[a].

Project name	AIV of 1:1 ratio in MWh/complex	AIV of 1: n ratio in MWh/complex	AIV of 1:1 ratio for optimal orientation MWh/complex	Difference in AIV of real 1: n ratio and optimal of 1:1 ratio in MWh/complex	Ratio of real AIV of 1: n to the optimal orientation AIV of 1:1
Jaff Towers	−29.729	−41.026	−29.388	−11.638	1.4
Danya Complex	−43.092	−64.638	−42.66	−21.978	1.52
Danya Complex	−42.682	−64.022	−42.66	−21.362	1.5
Goizha Complex	−68.228	−76.416	−67.782	−8.634	1.13

[a] Researchers, based on Table 9.

9- The cross section type (besides glazing) had minimal effect on optimizing the sustainable orientation, the variation ranged by 0.1%.
10- The QC is a fraction of QR which confirms that WWR is a very influential factor in determining the amount of heat transferred inside or outside through the envelope, the ratio of QC:QR was 1:5.7 for the baseline case.
11- Changing the WWR ratio from 30% to 20%, 25% and 35% changed the fraction of AIV transferred inside from 20.0% to 13.9%, 16.9% and 23.0%, respectively.
12- The fraction of AIV transferred inside increased by 62% (1.6 times) by changing the window from double to single pane glass.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2017.09.003.

References

Ali MM, Armstrong PJ. Strategies for integrated design of sustainable tall buildings. AIA report on university research. University of Illinois; 2006. [http://www.aia.org/aiaucmp/groups/ek_public/documents/pdf/aiap080038.pdf].

Cengel YA, Ghajar AJ. Mass and heat transfer: fundamentals and applications. Fifth edition. New York, NY: McGraw-Hill Education; 2015.

Council on Tall Buildings and Urban Habitat. A year in review: trends of 2011 skyscraper completion reaches new high for fifth year running, CTBUH Press Release January 18, Chicago IL; 2012 [http://www.ctbuh.org/LinkClick.aspx?fileticket=jxm6rltNs4I%3D&tabid=3040&language=en-US].

Elotefy H, Abdelmagid KS, Morghany E, Ahmed TM. Energy-efficient tall buildings design strategies: a holistic approach. Energy Procedia 2015;74:1358–69. https://doi.org/10.1016/j.egypro.2015.07.782.

Gane V, Haymaker J. Benchmarking conceptual high-rise design processes. CIFE technical report TR174. Stanford University; 2008. [October, http://cife.stanford.edu/node/139].

Ha PTH. A Concept for energy-efficient high-rise buildings in Hanoi and a calculation method for building energy efficiency factor. Procedia Eng 2016;142:154–60. https://doi.org/10.1016/j.proeng.2016.02.026.

International Energy Agency. World energy outlook, Paris; 2010. p. 90 [http://www.worldenergyoutlook.org/media/weo2010.pdf].

Jalal SJ, Bani RK. Impact of orientation of residential neighborhoods on optimizing sustainable and equitable exposure of insolation—case study of Sulaimani, Iraq. Energy Sustain Dev 2016;31:170–7. https://doi.org/10.1016/j.esd.2015.12.004.

Jovanovic A, Pejic P, Djorić-Veljković S, Karamarković J, Djelić M. Importance of building orientation in determining daylighting quality in student dorm rooms: physical and simulated daylighting parameters' values compared to subjective survey results. Energ Buildings 2014;77:158–70. https://doi.org/10.1016/j.enbuild.2014.03.048. [July].

Kavilkar R, Patil S. Study of high-rise residential buildings in Indian cities (a case study – Pune City). Int J Eng Technol 2014;6(1). https://doi.org/10.7763/IJET.2014.V6.671. [February].

Khan FR. Design of high-rise buildings, a symposium on steel. Chicago IL: ASCE, AICS Chicago Fabricators, University of Illinois; 1965 [Fall].

Knoke M. High-rise structures: life safety and security considerations. Protection of assets manual. Alexandria, VA: ASIS International; 2006. [https://booksite.elsevier.com/samplechapters/9781856175555/01~Front_Matter.pdf].

Lam JC, Chan RYC, Tsang CL, Li DHW. Electricity use characteristics of purpose-built office buildings in subtropical climates. Energ Conver Manage 2004;45:829–44. https://doi.org/10.1016/S0196-8904(03)00197-3.

Lau AKK, Salleh E, Lim CH, Sulaiman MY. Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: the case of Malaysia. Int J Sustain Built Environ 2016. https://doi.org/10.1016/j.ijsbe.2016.04.004.

Lechner N. Heating, cooling, lighting: sustainable design methods for architects. Third edition. New Jersey: Wiley; 2009.

Li J. Advanced supertall building design in hot-summer and cold-winter climates, CTBUH research paper. CBTUH 9th world congress Shanghai; 2012. [http://global.ctbuh.org/resources/papers/download/948-advanced-supertall-building-design-in-hotsummer-and-cold-winter-climates.pdf].

Ling CS, Ahmad MH, Ossen DR. The effect of geometric shape and building orientation on minimizing solar insolation on high-rise buildings in hot humid climate. J Constr Dev Countries 2007;12(1). [http://eprints.utm.my/7969/].

Lotfabadi P. Analyzing passive solar strategies in the case of high-rise building. Renew Sustain Energy Rev 2015a;52:1340–53. https://doi.org/10.1016/j.rser.2015.07.189.

Lotfabadi P. Solar considerations in high-rise buildings. Energ Buildings 2015b;89:183–95. https://doi.org/10.1016/j.enbuild.2014.12.044.

Mangkuto R, Rohmah A,M, Asri AD. Design optimization for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: a case study of buildings in the tropics. Appl Energy 2016;164:211–9. https://doi.org/10.1016/j.apenergy.2015.11.046. 15 February.

NASA Atmospheric Science Data Center. NASA surface meteorology and solar energy. [available] https://eosweb.larc.nasa.gov/cgi=bin/sse/grid.cgi?&num=058130&lat=39&submit=Submit&hgt=100&veg=17&email=wctauber@aol.com&p=grid_id&p=swv_dwn&step=2&lon=-123, 2005.

Raji B, Tenpierik MJ, van den Dobbelsteen A. An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates; a case study in the Netherlands. Energ Buildings 2015. https://doi.org/10.1016/j.enbuild.2015.10.049.

Stein RG. Observations on energy use in buildings. J Archit Educ 1977;30(3):36–41. https://doi.org/10.1080/10464883.1977.10758109.

Sulaimani Governorate, Military Grid Maps of Sulaimani, scale 1/25000, 1989. Weather Underground. BiZee degree days, weather data for energy professionals. http://www.degreedays.net/, 2014.