A Study of Daylighting Performance in Apartment Buildings with Reference to the Gaza Strip

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Abstract— Daylighting in residential buildings is an essential design parameter considering its impact on the visual comfort of users and energy efficiency of buildings. This is more challenging in apartment buildings, where collective residential configurations and deep plans are usually used. This is true in the case of the Gaza Strip, which makes daylighting quality in residential buildings a questionable issue. Thus, this study aims to examine daylighting performance in the Gaza Strip apartment buildings, and to propose some design recommendations to improve this performance. To achieve that, a simulation study has been carried out using Radiance program, where several cases have been examined. The study concluded that there is a direct relationship between the illuminance levels and space orientation, wall-to-window ratio, and reflectance of indoor surface materials. Also, light shelf has a crucial role in improving daylighting distribution in the space. The study therefore recommends applying these design strategies to improve daylighting performance and energy efficiency in the Gaza Strip apartment buildings. In this regard, a quantitative assessment may become part of the requirements of buildings licensing process..

Index Terms— Daylighting, passive design, apartment buildings, radiance, the Gaza Strip..

I. Introduction

Buildings consume a great deal of energy in the stages of construction and operation. Using fossil fuel for building operation, including lighting, produces greenhouse gases especially CO_2. This is believed to cause several damages to our planet such as global warming and environmental degradation. One way to mitigate these impacts is to rely on the passive design strategies of buildings. This includes investment of natural lighting, which can significantly contribute to energy savings in buildings. Moreover, it has a great potential to improve human visual comfort, health, and productivity, and offer an added value to the aesthetic characteristics of indoor spaces [1].

The above-mentioned notion is more critical in the case of the Gaza Strip. The Gaza Strip is located in the south-west area of the Palestinian Territories. It is a narrow strip that stretches along the eastern coast of the Mediterranean Sea. Gaza faces a great challenge in the energy sector. The ongoing energy supply shortage on one hand and the sunny climate on the other hand urge the use of passive design strategies including natural lighting. Thus, the purpose of this research is to investigate several design measures that are expected to help improving daylighting performance with reference to the apartment buildings of Gaza. The apartment buildings of Gaza were chosen because local architects today are under pressure from clients to design residential buildings with maximum space utilization. This is a direct result of the rising land prices in the Gaza Strip, which has a limited area of 365 km^2 and a rapidly growing population of about 1.8 M [2].

Thus, the challenge is to get daylight into all rooms including deep ones and those receiving natural light from light wells. This depends on some internal factors such as size and position of windows, depth and shape of the rooms, and colours of the internal surface. It also depends on some external factors including sky condition, solar radiation intensity, urban crowding, and amount of light reflected from adjacent structures. In this regard, several factors and solutions could be considered including orientation, window area, building materials colour and properties, and the use of natural lighting installations such as sun pipes and shelf devices [3].

There are several indicators that are used to quantify daylighting performance in buildings. This includes the daylight factor, which a measure of indoor daylight illuminance at a given location as a percentage of illuminance outdoors. It ranges from 0 to 100%, and sums up the three natural light components. These components are: sky component, externally reflected component, and internally reflected component [4]. Illuminance level may also be directly used. Illuminance of a surface is measured in lux, which is the incident flux density of 1 lm/m^2 [5].

Several studies have been carried out to assess daylight performance in buildings of different types. However, there is a need to carry further studies with reference to the Palestinian climatic conditions. For example, Ochoa and Capeluto [6] carried out a qualitative and quantitative evaluation of daylighting in office buildings. This is essential since acceptable daylighting levels can significantly improve working conditions and energy savings. Several systems that affect daylight penetration in the examined office spaces were analysed including a single window without any external protection and a horizontal light shelf. The effect of the indoor finishes materials reflectance was investigated too. These factors were simulated using Radiance program in a prototype building. The study concluded some guidelines for office building designers in climates with high solar radiation.

Kim, G., and Kim J. [7] examined the healthy-daylighting design for the living environment in the apartment buildings of Korea. They discussed the concept of healthy residential environment with reference to the role of natural lighting. Two actions were discussed in this regard: providing healthy light and eliminating harmful one within apartments. The role of balconies in shading and as a visual buffer space is confirmed to block excessive penetration of sunlight. This is useful to protect users from uncomfortable glare and UV penetration.

Chen *et al.* [8] carried out an experimental and simulation study on the performance of daylighting in in an industrial building and its energy saving potential. Daylighting illuminance was measured using 6*6 m grid in four periods on a sunny spring day. The daylighting simulations were done by Ecotect and Desktop Radiance simulation programs. Experimental and simulation results matched well. A further analysis was carried out to examine the energy saving potential of artificial lighting controls integrated with daylighting. This has been done using EnergyPlus program. The electricity saving potential for the examined controls integrated with daylighting was 36.1% and 41.5%.

II. THE MODELLING STUDY

The following sections explain inputs of the modelling study.

A. The Modelling Tool

As explained above, there is a need to improve daylight performance in buildings in order to maintain occupants comfort and enhance buildings energy efficiency. Improving daylighting performance requires the control of several design variables, which are expected to make a significant change. Thus, the use of computer simulation is a practical approach here, where there is a need to simulate several cases under different conditions. There are several tools that could be used to simulate daylighting performance in buildings. Radiance is one of these tools.

Radiance is a widely-used validated program used to estimate visible radiation distribution in three-dimensional illuminated spaces. Inputs include space geometry, materials properties, lighting source, time and date, and sky conditions. Outputs include illuminance levels, appearance of design spaces, and glare indices. Simulation results may be displayed as numerical values or contour plots [9]. Radiance modelling is based on a lighting ray tracing algorithm. Each single ray "carries" a certain amount of radiance. This starts from the viewpoint and then traces the rays up to the light sources taking into account light physical interactions including reflection and refraction [10].

B. The Modelling Cases

The modelling case is an apartment building composed of five residential floors and a commercial ground floor. The building is located in Gaza city, Palestine with a geographical coordinates of 31.52°N and 34.45°E. Each typical floor includes five flats, and four internal light wells, which imposes a challenge to achieve optimum internal daylighting conditions (Figure 1). The building is assumed fully exposed to daylighting with no shading devices on windows.

Considering the current study limitation, one living room and one space adjacent to a light well are examined (Figure 1), as follows:.

- Case-A: The first simulated space is a typical living room located in all the floors and oriented towards north. Space dimensions are 5.33m long, 4.45m width, and 2.85m high. Window opening is 1.8m and height is 1.1m. Typical internal finishing is assumed with the following reflectance values: 65% for walls, 35% for floor, and 68% for ceiling.

- Case-B: The second simulated space is a typical bathroom located in all the floors with a 0.6*0.6 window that opens into a 1*1.5 m light well. Space dimensions are 2.3m long, 1.2m width, and 2.85m high. Typical internal finishing is assumed with the following reflectance values: 80% for walls, 35% for floor, and 68% for ceiling. As for the light well, reflectance is assumed 30%, assuming unfinished concrete walls.

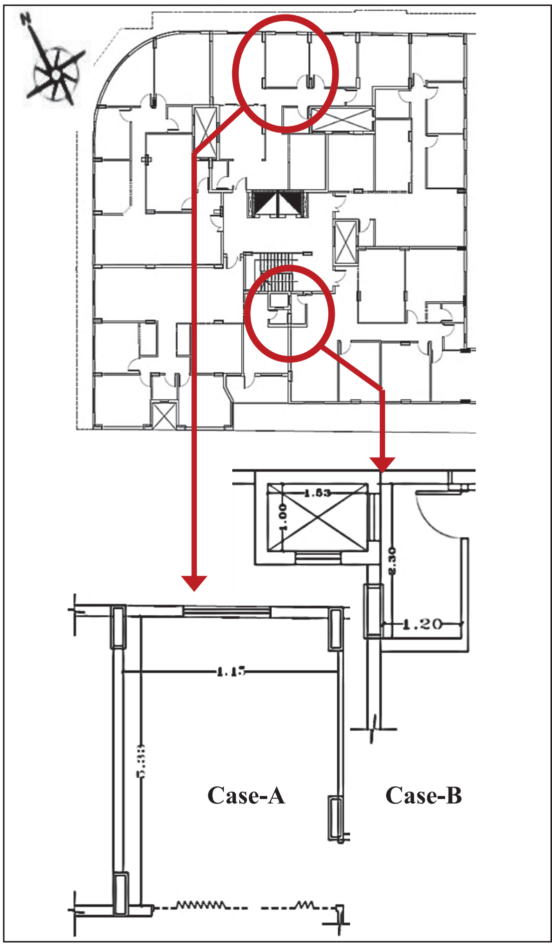


Figure 1: The examined cases in the modelling study

C. The Modelling Settings

Indoor daylighting is assessed through calculating illuminance levels, which indicate the quality of the indoor daylighting. Radiance has been used in this regard to evaluate indoor daylighting in the simulated room at the five different floors. A reference grid was assigned in the simulated room by allocating sensors grid at 1 m above the floor. In all cases, a grid of uniformly distributed nine sensors was used to calculate illuminance level (Figure 2).

The middle line of the grid adopted as the average. As mentioned above, the sensors were placed at 1 m height measured from the floor. Modelling has been carried out considering noon time conditions at the 21st of March, which represent balanced ambient conditions. Daylighting studies are usually carried out considering overcast sky as the worst scenario. However, it is usually clear in the Gaza Strip. So, the simulation has been carried out under a clear sky condition.

A number of variables concerning natural lighting design and elements have a potential impact on daylighting performance. Considering study limitations, the following variables have been examined:

- Case-A: orientation, window-to-wall ratio, material reflectance and using a light shelf.
- Case-B: light well orientation, light well area, window-to-wall ratio, and material reflectance.

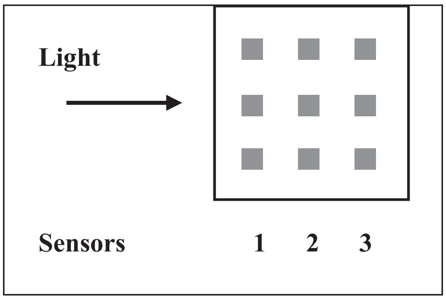


Figure 2: A grid of uniformly distributed nine sensors is used to calculate indoor illuminance level

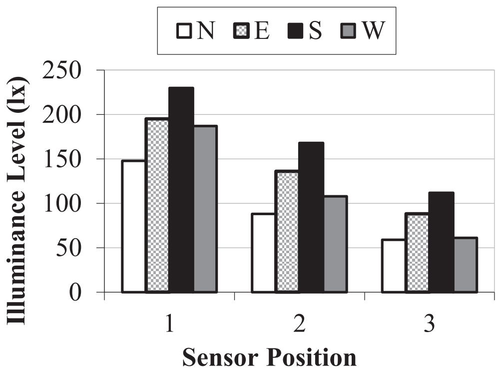
III. Results and Discussion

Modelling has been carried out for both cases considering the above-mentioned variables. An optimisation approach has been adopted, where the best case in each test is forwarded for further improvement in the next test. As mentioned in the modelling settings, all results have been recorded at 12:00 pm in the 21st of March and under clear sky conditions. In order to read results in a practical way, it is useful to mention that recommended illuminance levels vary depending on the task. For residential buildings, this varies between 200 lux for rough tasks and large details, e.g. kitchen, to 400 lux for ordinary task and medium details, e.g. reading [5].

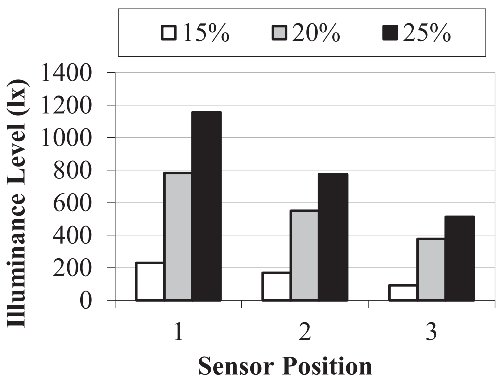
A. Case-A

The living room has been modelled in the different main directions to examine orientation effect on the indoor illuminance level. Figure 3-a represents the illuminance level in the simulated room. The results show that the southern orientation is always the best case regardless sensor positioning. Orientation towards the south offers a significant increase in illuminance level that reaches 50% when compared to the north orientation.

Figure 3-b shows the effect of increasing window area on the illuminance level, where southern orientation is implemented. This increase is represented as a ratio to the floor plan area. The Figure shows a stepped pattern of results. This means that illumination level is proportional to window-to-wall ratio. Results show that increasing window-to-wall ration from 15% to 25% caused a dramatic increase in illuminance levels from about 170 to 775 lux.



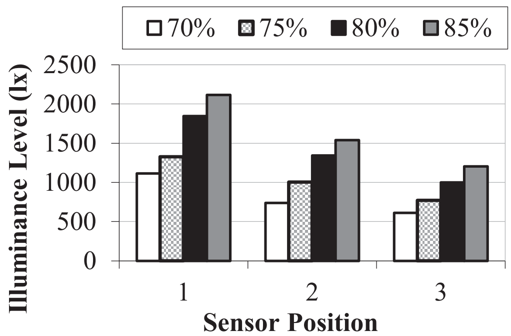
a. Window orientation



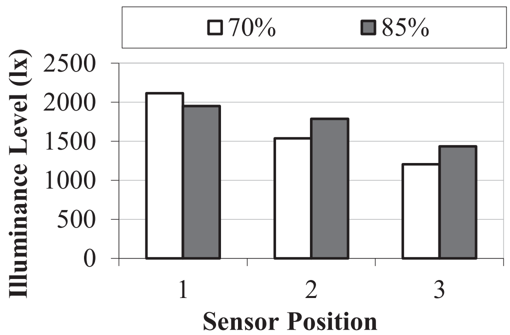
b. Window-to-wall ratio

Figure 3: Illuminance levels (lux) in Case-A considering different orientations and window-to-wall ratios

The third variable is material reflectance. Material reflectance has been investigated considering the best conditions resulted from the previous two variables. These conditions are: window-to-wall ration of 25% (1.5m height by 2.0m width), and a southern window orientation. The simulation was carried out by changing the material reflectance incrementally by 5% (starting from 70% and reaching 85%). Figure 4-a shows the obtained results. Generally, the results show that increasing material reflectance helps to improve the daylight environment in the simulated space. The illuminance level has increased gradually and systematically. Increasing reflectance value from 70% to 85% offers a significant increase in illuminance level that exceeds 100%.



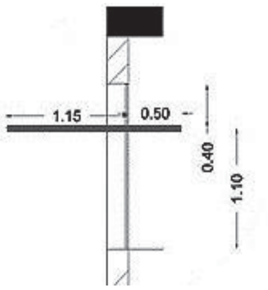
a. Indoor materials reflectance



b. The use of light shelf considering two reflectance values

Figure 4: Illuminance levels (lux) in Case-A considering different values of finishing material reflectance and the use of light shelf

Finally, the effect of using a light shelf in the room has been examined. A light shelf has been added to the window (Figure 5). This has been tested considering the best conditions resulted from the previous tests, i.e. 25% window-to-wall ration, and a southern window orientation. This has been tested for reflectance value limits that were used in the previous test, i.e. 70% and 85%. Figure 4-b shows the results obtained. Generally, results show that the light shelf helped to improve the daylight environment in simulated space. The difference between illuminance level deep in the room (sensor position 3) and near the windows (sensor position 1) has been significantly reduced compared to the results of the previous test. As shown in Figure 5, adding a light shelf reduces illuminance value near the window by 8% but improves lighting performance in the deep parts of the space by 15%. This has led to improve the daylight quality by increasing its uniformity level in the space.



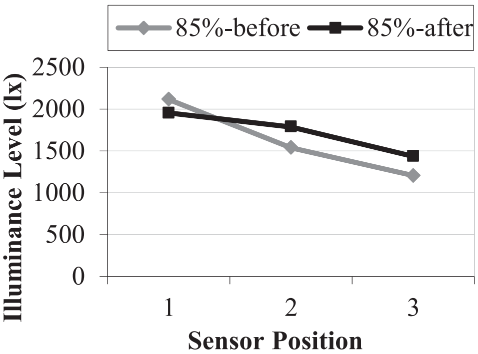


Figure 5: Illuminance levels (lux) in Case-A before and after adding the light shelf for 85% material reflectance

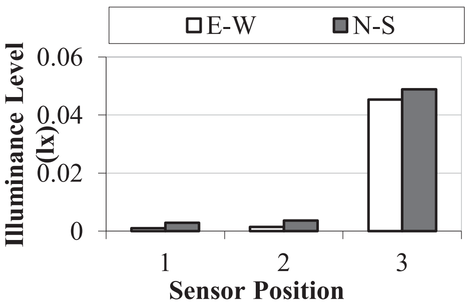
B. Case-B

Firstly, orientation of the light well is examined. Two orientations have been examined: north-south and east-west. Window dimensions have been maintained in both cases. As illustrated in Figure 6-a, results show the both cases have presented similar daylighting performance with a slight difference. The low value recorded for illuminance level indicates that daylighting performance in this case requires further improvement.

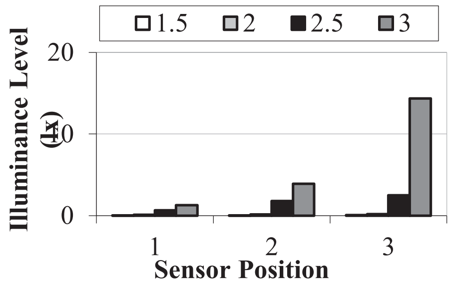
To do so, four light well areas have been examined:

- Area multiplying factor of 1.5 (2.3*1.5 m).
- Area multiplying factor of 2.0 (3.1*2.0 m).
- Area multiplying factor of 2.5 (3.8*2.5 m).
- Area multiplying factor of 3.0 (4.6*3.0 m).

Window dimensions have been maintained with N-S orientation of the light well. Base case plan area was about 1 m^2 (1*1.53 m). Four alternatives with different plan areas were tested. To do so, the base area has been multiplied by incremental factors as follows: 1.5, 2, 2.5, and 3, keeping in mind that light well aspect ratio is fixed. Figure 6-b illustrates the results that represent the effect of the light well area increase (represented by the multiplying factor) on the indoor illuminance level. The results show a slight increase in the indoor illuminance level, which is proportional to the light well area increase in an exponential manner. However, this increase didn't reach an acceptable level compared to the standard value for residential buildings (200-400 lux). It is also possible to note that illuminance value increased more rapidly as x multiplying factor of the light well area increases.



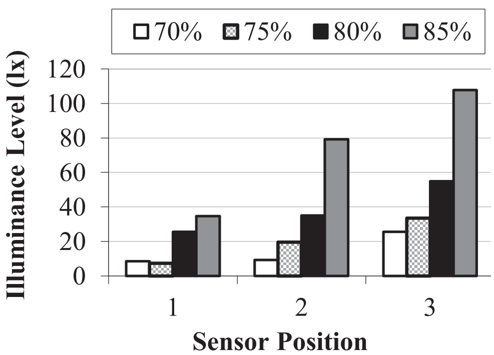
a. Light well orientation



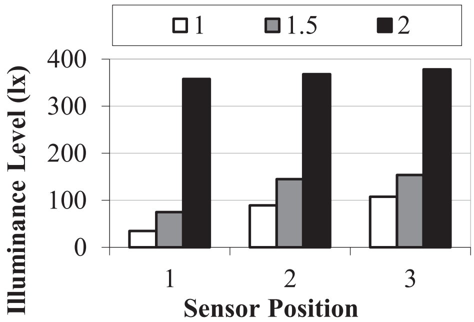
b. Light well area (multiplied by different factors)

Figure 6: Illuminance levels (lux) in Case-B considering different light well orientations and plan areas

The third variable examined in Case-B is indoor material reflectance. This has been investigated considering the best conditions resulted from the previous two variables. These conditions are: light well area multiplying factor of 3, and a north-south orientation of the light well. The simulation was carried out by changing the material reflectance incrementally by 5% (starting from 70% and reaching 85%). Figure 7-a shows the obtained results. Generally, the results show that increasing material reflectance helps improving the daylight performance. For each reflectance value, the increase is significant and systematic. Considering sensor position 2 as an average, increasing reflectance value from 70% to 85% offers a significant increase in illuminance level from 9 to 80 lux. It is also possible to note here that the effect of increasing reflectance is more significant when compared to Case-A (Figure 4-a). This can be justified by the fact that natural lighting in Case-B relies on the reflected radiation supplied by the light well, which makes the role of materials reflectance more critical.



a. Indoor materials reflectance



b. Light well window area (multiplied by different factors)

Figure 7: Illuminance levels (lux) in Case-B considering different values of material reflectance and light well window area

Finally, the effect of increasing window area has been examined. Window area has been multiplied by the following factors keeping its aspect ratio fixed: 1, 1.5, and 2. The simulation has been carried out for the best conditions observed in the previous three variables, i.e. N-S orientation of the space, plan area multiplying factor of 3, and indoor materials reflectance of 85%. Figure 7-b shows that increasing the opening area is the most effective design measure in the case of natural lighting using light well.

Doubling area of the light well window dramatically increases illuminance level from 90 to about 370 lux. However, this requires careful design to maintain users' privacy. For example, the required opening area may be provided as two medium sized windows instead of a large one. Alternatively, the required opening area may be provided as a strip window rather than a square one in order to ensure better daylight distribution in the space, especially in the corners.

IV. CONCLUSION

Daylighting in residential buildings is an effective passive design strategy that enhances energy efficiency of buildings. This is more challenging in collective residential configurations such as apartment buildings. Thus, the aim of this study was to investigate several design measures that help improving daylighting performance with reference to the apartment buildings of the Gaza Strip. In this regard, several strategies have been numerically investigated using Radiance modelling tool. This includes orientation, window area, materials reactance, and the use of light shelf devices. An optimisation approach has been adopted, where the best case in each test is forwarded for further improvement in the next one. Results showed that using natural lighting in residential buildings is an effective strategy in providing acceptable indoor illuminance levels. This has a potential to improve energy efficiency in these buildings. However, this requires careful design of several parameters such as openings sizing, shading, and orientation.

As for the case receiving daylighting through external windows (Case-A), results showed that higher illuminance levels can be obtained near the window (sensor position 1). This is due to the direct light intensity that passes through the window. The following findings have been observed:

- Orientation towards the south offers a significant increase in illuminance level that reaches 50% when compared to the north orientation. However, it is essential in this case to avoid unwanted direct solar lighting through using appropriate shading devices.
- Increasing window-to-wall ration from 15% to 25% caused a dramatic increase in illuminance levels from about 170 to 775 lux.
- Increasing reflectance value from 70% to 85% offers a significant increase in illuminance level that exceeds 100%.
- Adding a light shelf reduces illuminance value near the window by 8% but improves lighting performance in the deep parts of the space by 15%.

As for the case receiving daylighting via a light well (Case-B), results showed that higher illuminanc levels can be obtained far from the window (sensor position 3). Unlike Case-A, this is due to the shaded areas that results behind the indirect lighting cone admitted by the window. The following findings have been observed:

- Changing light well orientation doesn't seem to have a significant effect on illuminance level. This is also true for increasing light well area without increasing window area.
- The role of finishing materials reflectance is significant. Increasing reflectance value from 70% to 85% offers a significant increase in illuminance level from 9 to 80 lux.
- The most significant case is increasing window area. Doubling area of the light well window dramatically increases illuminance level from 90 to 370 lux.

In general, the above-mentioned design measures have been found to significantly improve indoor daylighting conditions by increasing indoor illumination levels. The study therefore recommends carrying out a quantitative assessment of lighting performance in the apartment buildings in the design stage. This may become part of the requirements of buildings licensing process. In this regard, it is recommended to carry out further studies to investigate the effect of changing orientation and window-to-wall ratio on the expected cooling demand and glare levels. Further design variables may also be examined including urban design inputs, and additional testing dates and hours of the day.

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