

Impact of School Building Geometry on Energy Performance and Thermal Comfort in Hot-Arid Climates: A Case Study of Governmental Elementary Schools in Cairo

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Abstract:

In the last decade, the government interest in the educational process reached its first priority, especially the elementary schools. That's why the ministry of education has built a reasonable number of schools in the recent years in different parts of governorates and villages too. In addition, the government is granting a number of indulgences to support the private sector to increase the number of schools with various curriculums to fulfill the demands of different classes in the society

Basically, Poor thermal comfort in schools can negatively affect children's health and academic performance [1], that's why evaluating different school design parameters becomes crucial for ensuring both energy efficacy and improved occupant comfort.

School buildings in Cairo exist in various typologies with different parameters that affect thermal comfort. For this study, the researchers selected three common shapes frequently used in governmental schools, which are, L-shape, linear shape, and the court shape. the research discusses the role of geometrical parameters including building shape with constant window to wall ratio, room depth, and orientation on the energy use and thermal comfort of school buildings in hot climates of Cairo. Furthermore, it discusses summer thermal discomfort times which is compared through computer simulations with **Design Builder**.

The results of the research arranged shapes according to their energy Performance and Thermal Comfort, and the research proves that all shapes have definite problems in thermal comfort in certain months, which needs special adaptation to the typologies as a whole.

The results of the research can be an applicable reference for architects in their early stages of school designs which maintain a higher thermal comfort for young students in Cairo.

Keywords: school design; geometrical parameters; energy consumption; thermal comfort.

1. Introduction

In recent years, the educational sector in Egypt has witnessed significant growth, with the government prioritizing the expansion and development of school infrastructure across the country. This surge in school construction is particularly evident in the Greater Cairo Region (GCR), where the demand for educational facilities is high due to the region's dense population. Both public and private sectors have played crucial roles in addressing this demand, leading to a

diverse types of schools designed to accommodate various educational curriculums and social classes.

Despite the rapid expansion, the design of many new school buildings has not adequately addressed environmental considerations, particularly in terms of energy efficiency and thermal comfort. Schools in hot arid climates, like those in Cairo, face unique challenges due to extreme temperatures, which can significantly impact the learning environment. The thermal discomfort experienced by students and staff during the hot summer months is a crucial concern, as it can affect concentration, productivity, and overall well-being. While this research concentrates on the influence of geometrical configuration as a major design parameter, it is essential to acknowledge that other interconnected factors also influence thermal comfort and energy use. Material properties, building orientation, natural ventilation approaches, and even the behavioral patterns of users contribute significantly to the energy efficiency of educational buildings. This research isolates geometry as a controlled variable to clarify its impact, yet it also emphasizes the importance of viewing school performance as a result of multiple design decisions working in harmony. A more comprehensive understanding of these interactions can lead to more realistic and reliable design outcomes for future developments in hot arid regions [2]

2. Research aims and objectives

The primary objective of this research is to explore the impact of different geometrical configurations on the energy performance and thermal comfort of school buildings in the GCR. By utilizing computer simulations with **Design Builder**, this study seeks to identify building design that can enhance thermal comfort and reduce energy consumption in educational facilities. The findings aim to provide architects and planners with actionable insights that can be applied during the early stages of school design, leading to more sustainable and comfortable learning environments for students.

3. Energy and Thermal Performance in School Buildings

Energy consumption in educational buildings is highly crucial within sustainability nowadays, specially within the global trend towards energy-efficient designs and the reduction of carbon emissions. Schools, universities, and other educational institutions are high energy consumers due to their size, occupancy rates, and various uses [3]. In recent years, numerous studies have focused on understanding the drivers of energy consumption in these buildings and identifying ways to optimize their performance.

3.1 Building Design and Architecture

The architectural design of educational buildings significantly impacts their energy consumption. Studies indicate that compact building shapes tend to minimize heat loss and gain, making them more energy-efficient compared to irregular or elongated designs [3]. Additionally, buildings with larger window-to-wall ratios and minimal insulation often experience higher energy consumption due to increased thermal exchange between the interior and exterior environments [4].

3.2 Climate and Location

The geographic location and climatic context of schools have a profound influence on their heating, ventilation, and air conditioning (HVAC) demands. In hot, arid regions, a certain share of energy resources is allocated to cooling and ventilation in order to maintain a comfortable and healthy learning environment for students [3]. Research suggests that adaptive architectural

strategies, which respond to local climatic variables such as solar radiation, wind direction, and temperature fluctuations, can significantly reduce energy use while improving thermal comfort [4]

3.3 Occupancy Patterns and Behavior

The cyclical occupancy patterns of schools also play a crucial role in their energy profiles, with peak energy demand typically occurring during daytime school hours [5]. However, inefficient management of HVAC and lighting systems during off-hours or holidays can result in excessive energy consumption. Studies indicate that promoting energy-conscious behaviors among building users, along with implementing smart energy management systems, can substantially reduce overall energy consumption

3.4 Energy Efficiency Technologies

The integration of energy-efficient technologies has become more common in educational settings. Retrofitting older school buildings with technologies such as LED lighting, high-efficiency HVAC systems, and photovoltaic solar panels has shown potential to reduce energy consumption by 30-50% [1]. Additionally, smart building systems, including automated controls for lighting and HVAC based on real-time demand, have demonstrated effectiveness in further optimizing energy use.

3.5 Geometrical Parameters and Building Performance

Designing buildings that can enhance the users' thermal comfort, energy consumption levels, and CO₂ emissions start from their footprint on their environment. Given that there is a significant relation between the Indoor Environmental Quality of buildings and the outdoor urban thermal performance. This includes many variables; however, the study will only focus on buildings' forms. The building form is the first step in reaching thermal comfort and energy efficiency and decreasing CO₂ emissions, thus, simultaneously decreasing its footprint on its environment. Hence, this part is dedicated to analyzing the effect of the different building geometrical forms on all three elements with their implication on orientation, which will be presented in the Empirical study.

4. Empirical study

4.1 Methodology

This research adopts a quantitative approach to examine how various geometrical parameters affect energy consumption and thermal comfort in elementary school buildings within Cairo's hot climate. A reference case school building is modeled as a baseline for comparison. Using **Design Builder** software, a series of computer simulations are conducted to analyze the impact of each geometrical school shapes which was previously designed by the Egyptian educational buildings institution on energy efficiency and thermal comfort levels. Simulation results are then evaluated against the baseline model to quantify potential improvements. Based on these findings, the study concludes with practical design recommendations that can be implemented by architects to optimize energy use and enhance thermal comfort in Cairo's school buildings.

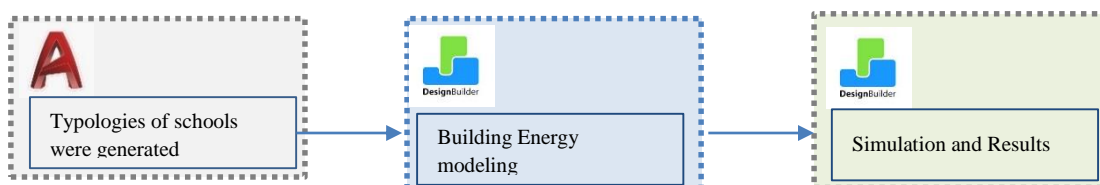


Figure 1: simulation workflow of the school buildings typologies, (Authors,2025)

4.2 School building Standards

Schools in Egypt have certain standards based on the **General Authority for Educational Buildings (GAEB)**, for instance, the classrooms which have the highest significance in the school should follow certain rules. Each classroom should have a minimum area of 38 square meters, with a maximum length of 8.5 meters to ensure that even the furthest students can view the blackboard clearly, and the closest seats remain within the ideal viewing angle. According to the Institute, window areas should constitute no less than 20% of the classroom space and be positioned on one side to enhance natural lighting. Doors require a minimum width of 1 meter, while window sills should not exceed a height of 1.10 meters, providing optimal sightlines and accessibility. Furthermore, it is preferable for lighting to enter from the left side of the students to reduce shadows and enhance visual comfort.

4.3 Schools Building Models

The Egyptian Educational building has a number of typologies of school buildings, yet, the commonly used in GCR are three types only which are, **The I shape, the L shape, and the Court shape**, as shown in fig.2. Thus, the researchers used the 3 types for simulation as the chosen shapes are the most implemented in GCR with a percent of 78% according to the (GAEB).

To study the 3 types, the Three school building models were built in **Design Builder**. Each of the seven archetypes had the same spatial composition: general classroom, specialized classroom, bathroom, and circulation space. Moreover, the size and numbers of different kinds of rooms were kept identical for each configuration.

The specific components for these rooms are presented in Table 1, according to local norms. Moreover, the size and numbers of different kinds of rooms were kept identical for each configuration. The width of the corridor was set at 3 m for double loaded corridor and 2.5m for single loaded corridor according to (GAEB) rules.

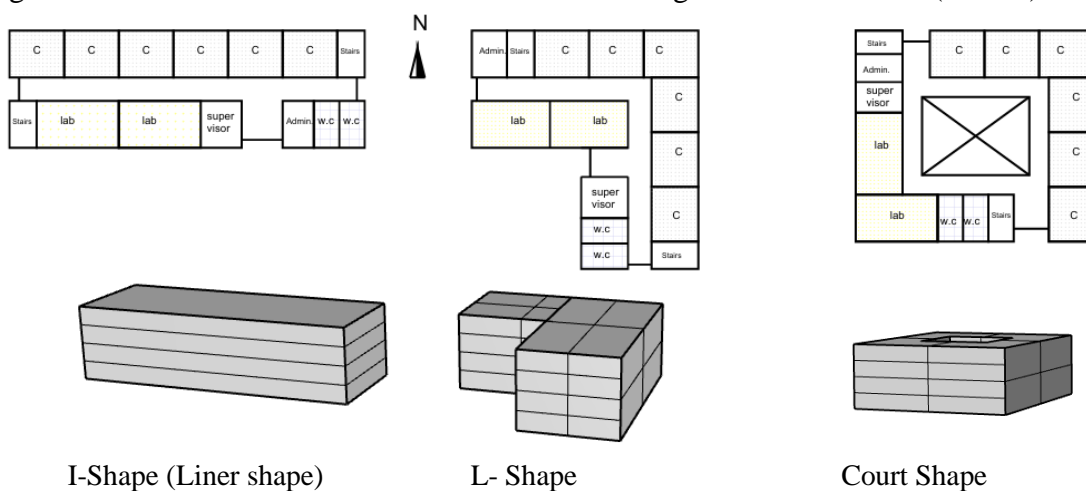


Figure 2: Shows modes of the three types of the school buildings source: (GAEB edited by Authours,2025)

Table 1: spatial configuration of the three school building prototypes

Components	Count	Area (m ²)	Total Area (m ²)
Classroom	22	42	924
Laboratories	3	60	180
Computer lab	1	60	60
Art room	1	60	60
Music room	1	60	60
Agriculture room	1	60	60
Multi-Purpose Hall	2	80	160
Library	1	100	100
Supervisors' Rooms	3	24	72
Offices	6	20	120
Entrances	2	24	48
Stairs	2 * 4stories	21	168
Toilets	2 * 4stories	18	144

4.3.1 The I shape simulation

Within the **Design Builder** software, a detailed 3D model of the school building was developed to evaluate its thermal performance and energy efficiency. At the beginning, the I shape school is

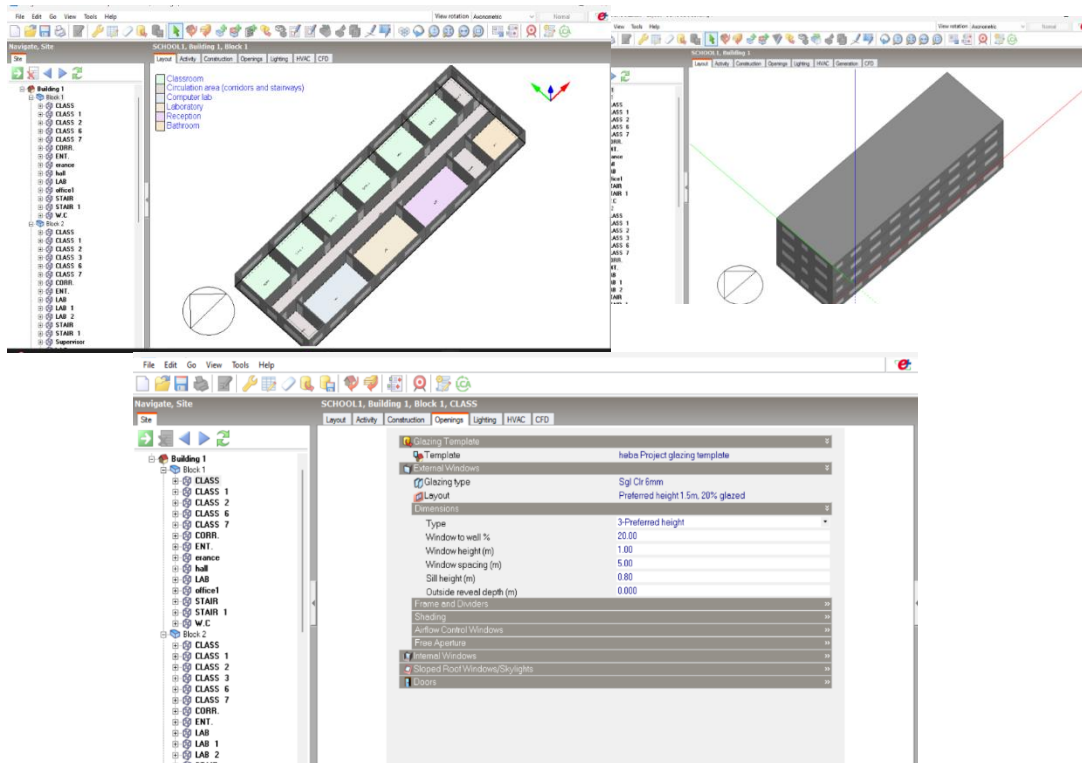


Figure 3: 3D model and simulation setup of a linear-shaped school building in DesignBuilder, showing classroom layout, external form, and glazing/window configuration parameters, (Aurhors,2025).

modelled defining the structure’s spatial layout, including classrooms, corridors, computer labs, and bathrooms. **Fig 3**, highlights the allocation of internal zones, with the previously defined spaces for different functions. Within the modelling, specifications for window glazing were set following the standards provided by the **General Authority of Educational Buildings (GAEB)**. The design utilized 6mm single glazing with a 20% glazed window-to-wall ratio, the preferred height 1.5 meters, and window sill height 0.8

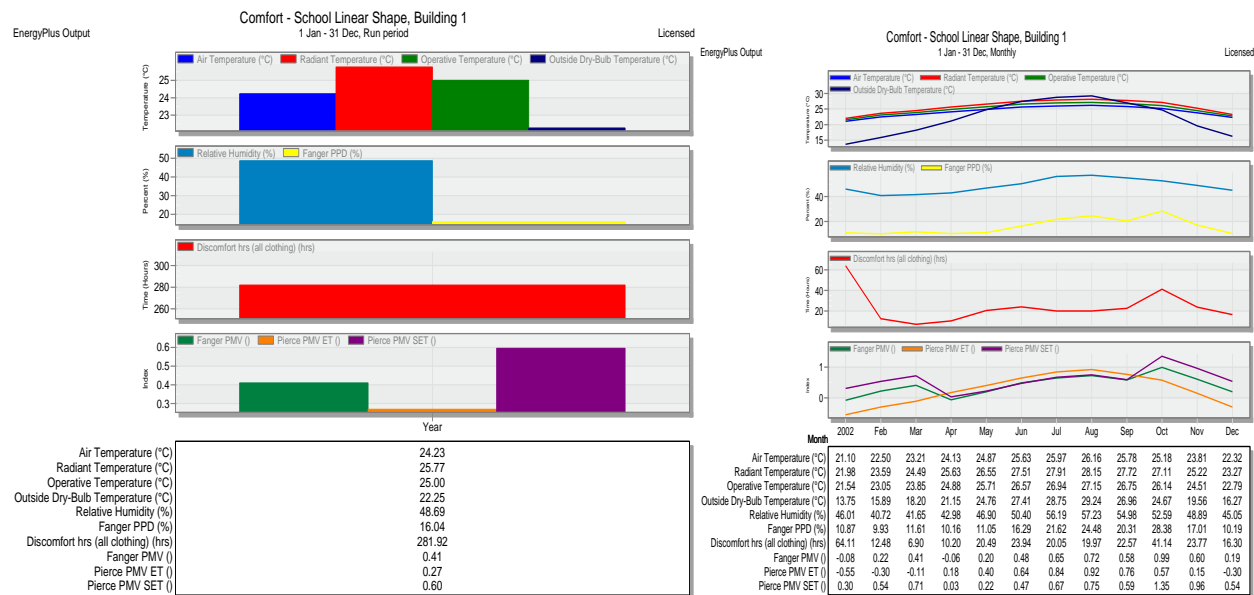


Figure 4: EnergyPlus simulation of a linear-shaped school building showing annual and monthly variations in temperature, humidity, and comfort indices (PMV and PPD), (Aurhors,2025).

4.3.2 The L shape simulation

The L-shape school was modeled in Design Builder following the **General Authority of Educational Buildings (GAEB)** prototype, using the same parameters as the I-shape (area, zoning, and floors). The internal layout was adapted to the L-configuration, and glazing specifications matched **GAEB** standards with 6mm single glazing, a 20% window-to-wall ratio, and a 1.5m window height.

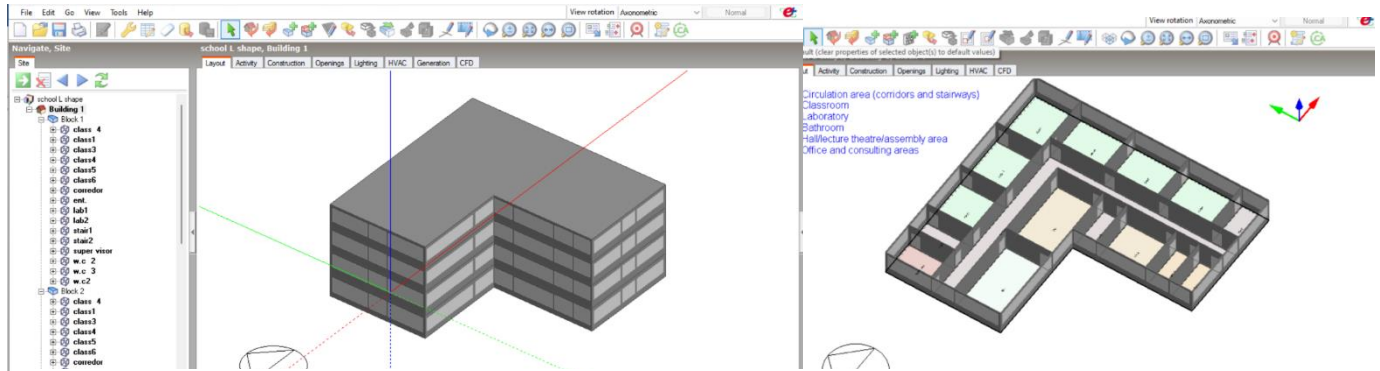


Figure 5: 3D model and simulation setup of a L-shaped school building in DesignBuilder, showing classroom layout, external form, and glazing/window configuration parameters, (Aurhors,2025).

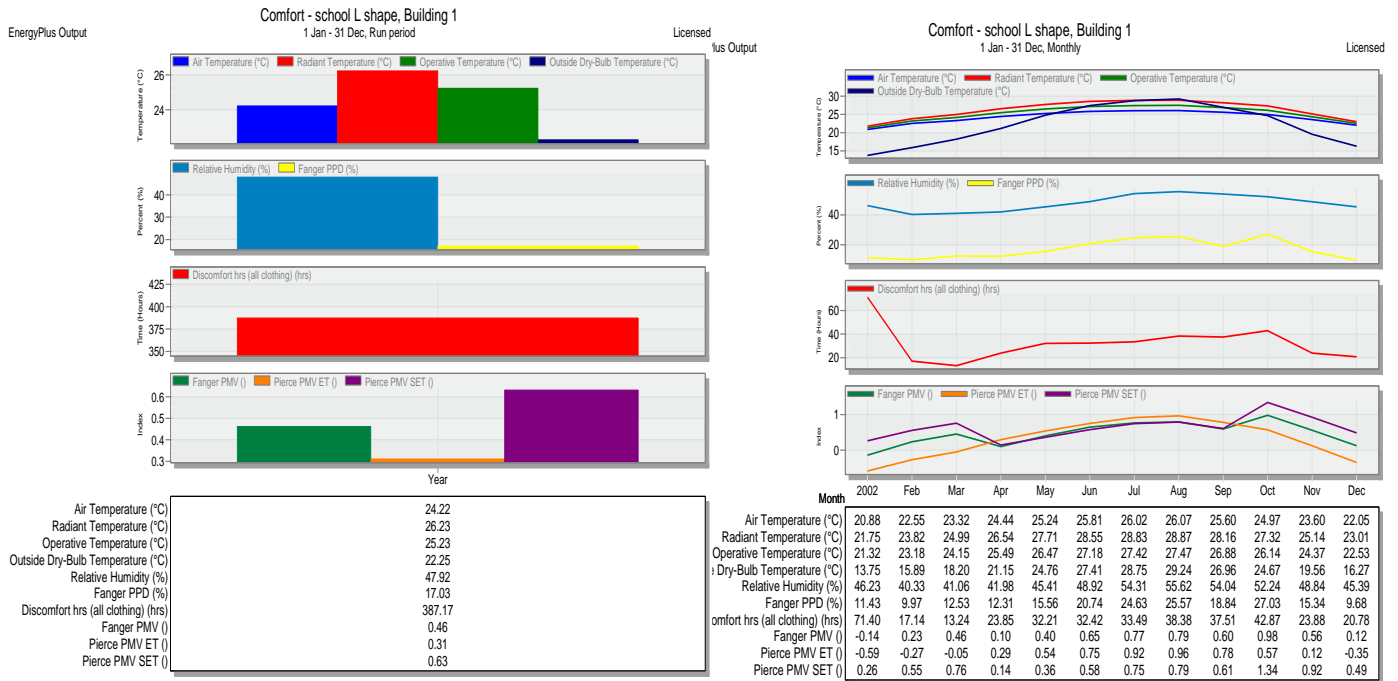


Figure 6: EnergyPlus simulation of a L-shaped school building showing annual and monthly variations in temperature, humidity, and comfort indices (PMV and PPD), (Aurhors,2025).

4.3.3 The Court Shape

The last shape is the court shape according to the (GAEB) prototype

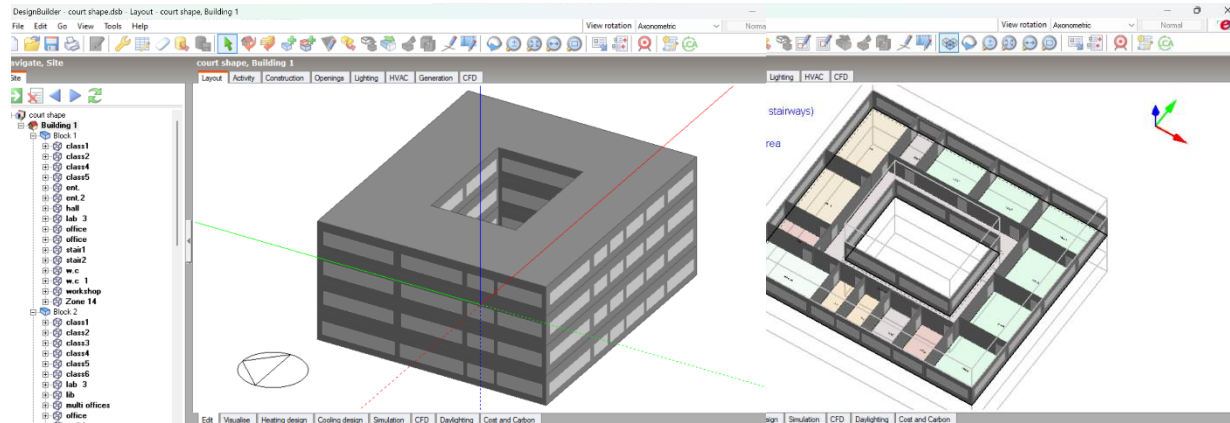


Figure 7: 3D model and simulation setup of a Court-shaped school building in DesignBuilder, showing classroom layout, external form, and glazing/window configuration parameters, (Aurhors,2025).

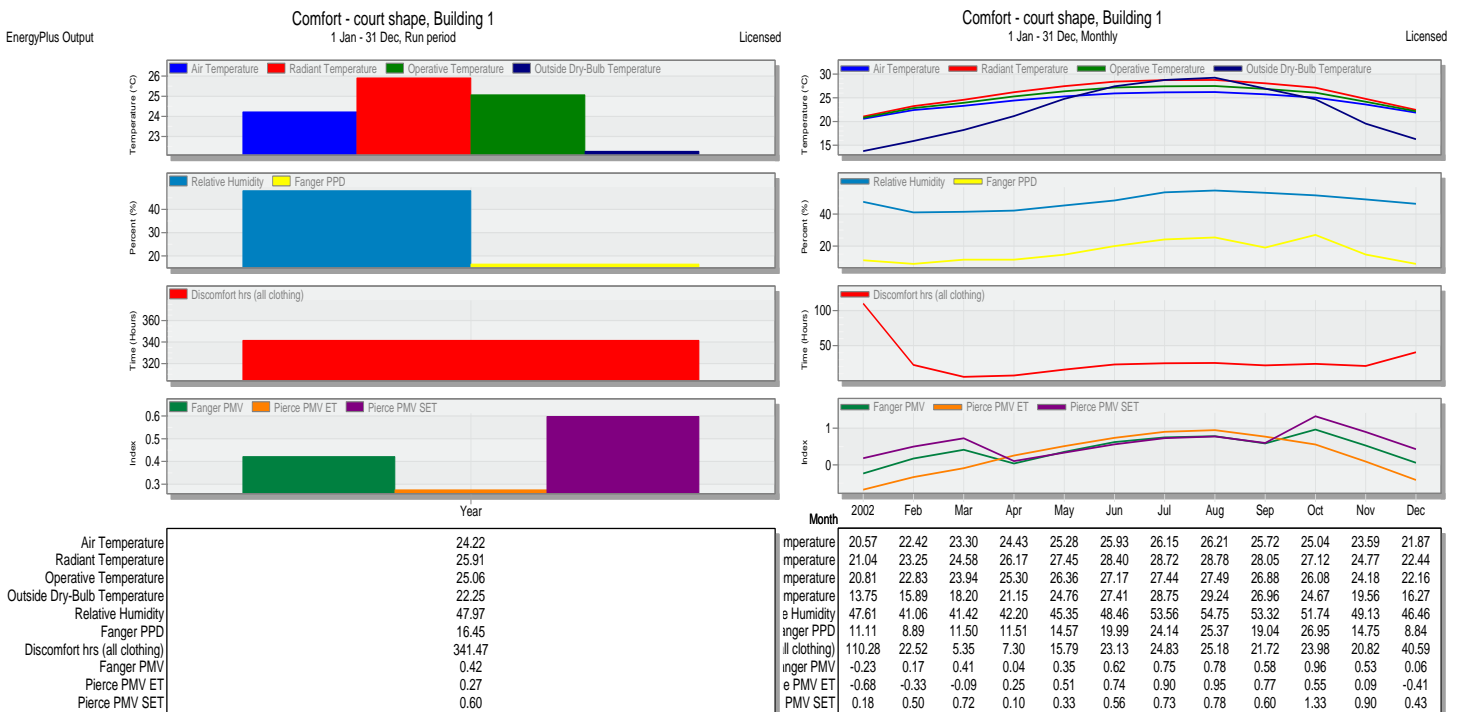


Figure 8: EnergyPlus simulation of a court shaped school building showing annual and monthly variations in temperature, humidity, and comfort indices (PMV and PPD), (Aurhors,2025).

To evaluate and compare the environmental performance of three educational building prototypes (courtyard, L-shape, and linear) located in Egypt, using the weather file of Cairo airport station.

the following simulation assumptions were adopted:

- **Cooling System:**
Mechanical cooling was activated in all three models to reflect the common use of air-conditioning in Egyptian educational buildings during the hot season. This setup enables an accurate estimation of cooling energy demand, which is a critical concern in Egypt's hot arid climate.
- **Heating System:**
Mechanical heating was excluded from the simulations, as heating systems are rarely installed in educational buildings in Egypt. This decision allows the analysis to focus on relevant energy demands and thermal comfort without skewing results with heating loads that are not typically part of the local building operation.
- **Natural Ventilation (NV):**
All prototypes were simulated with natural ventilation to represent realistic mixed-mode operation. This approach shows typical building use, where windows or openings are utilized during milder seasons or nighttime to reduce mechanical cooling needs. It also allows evaluation of indoor air quality and ventilation effectiveness, including CO₂ concentration levels.
- **Materials**

External wall

- External Cement/plaster/mortar-cement/lime plaster 2 cm
- Brickwork 25 cm
- Internal Cement/plaster/mortar-cement/lime plaster 2 cm

Internal wall

- External Cement/plaster/mortar-cement/plaster 2 cm
- Brickwork 12.5 cm
- Internal Cement/plaster/mortar-cement/plaster 2 cm

Roof

- Roof Tile 2 cm
- Cement/plaster/mortar-cement plaster 2 cm
- Loose fill/powders-sand 5 cm
- Cast Concrete (Lightweight) 7 cm
- Thermalite - High Strength 5 cm
- Foam-poly isocyanate 3 cm
- Concrete Slab 20 cm
- Cement/plaster/mortar-cement plaster 2 cm

Floor

- Cement/plaster/mortar-cement plaster 2 cm
- Loose fill/powders-sand 5 cm
- Concrete Slab 20 cm
- Cement/plaster/mortar-cement plaster 2 cm

4.4.5 Standardization Across Prototypes

To ensure fair and scientifically valid comparison, all environmental systems, control strategies (temperature setpoints, operation schedules, ventilation settings), and simulation parameters were standardized across the three models.

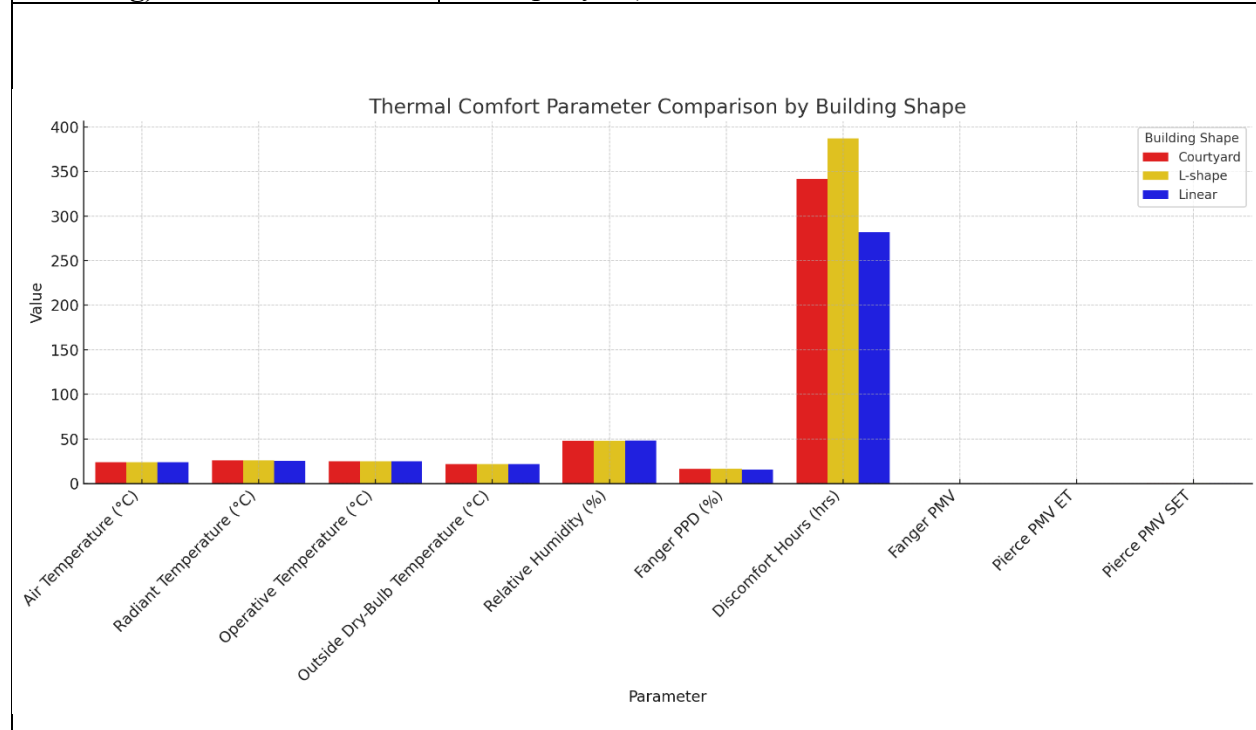
This configuration allows a focused and realistic analysis of cooling loads, thermal comfort (Fanger PMV/PPD, discomfort hours).

4.6 Results & Visuals

The following parameters summarize energy efficiency and occupant comfort outcomes across the three prototypes, presented through tables, charts, and thermal maps for comparative analysis. Comfort is assessed using Fanger’s indices: PMV (thermal sensation), PPD (percentage of dissatisfied occupants), and discomfort hours, based on ASHRAE Standard 55 thresholds.

Table 2: Output Type and Data for each prototype

Output Type	Data
Energy Use	Total Energy (kWh/m ² /year), Cooling loads
Thermal Comfort	Fanger PMV, Fanger PPD, Discomfort hours (ASHRAE Standard 55)
Temperature Distribution	Indoor temperature profiles and spatial variation
Fanger PMV	PMV between -0.5 and +0.5 is considered thermally neutral.
Fanger PPD	under 20% dissatisfied is typically the threshold for comfort compliance.
Discomfort Hours (All Clothing)	Number of hours outside the comfort range (out of 8,760 hours per year).



4.6.1 Monthly Operative Temperature Analysis by Building Shape

As shown in **fig.9**, The **linear shape** maintains the lowest operative temperatures throughout the year, showing superior thermal performance. The **L-shape** records the highest values, reflecting greater heat accumulation, while the **Court shape** remains intermediate. Temperature differences across forms are modest ($\approx 0.5\text{--}1\text{ }^{\circ}\text{C}$) but remain significant for thermal comfort and cooling loads.

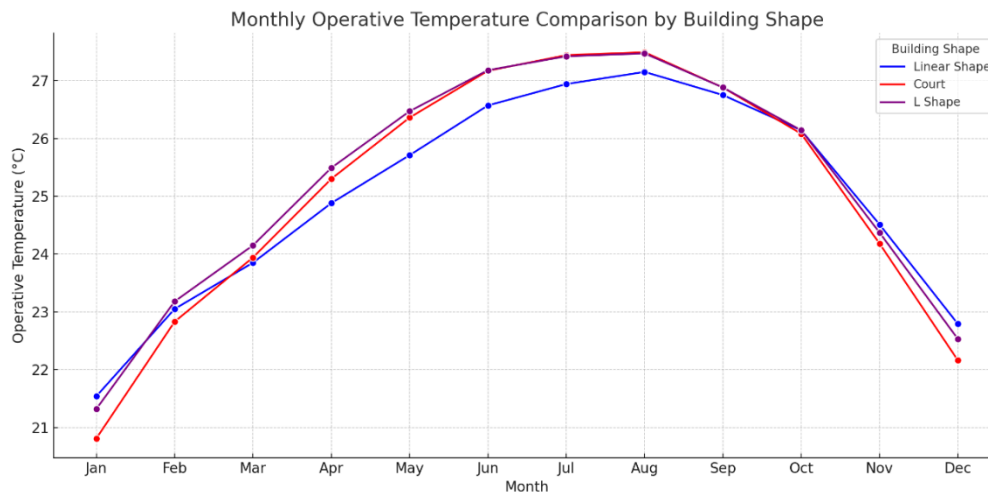
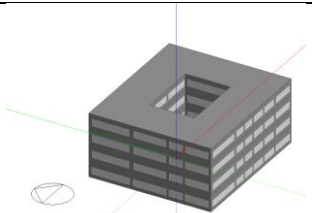
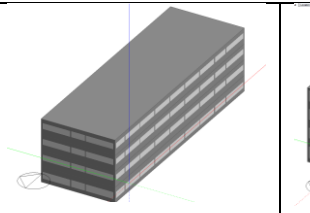
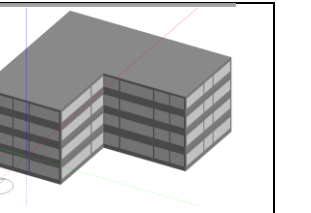


Figure 9: the monthly operative temperature comparison by of the 3 selected typologies, (Aurhors,2025).

Table 3: Comparative Analysis of Energy Performance and Thermal Comfort Across Educational Building Prototypes, (Aurhors,2025).

			
Total Energy Use and Intensity	266.44 kWh/m ² /year (+5.7%)	251.97 kWh/m ² /year	295.78 kWh/m ² /year (+17.4%)
Cooling Load	521,643.19 kWh/year (+6.9%)	488,102.79 kWh/year	595,260.81 kWh/year (+21.9%)
HVAC Energy Use per Unit Area	219.9 kWh/m ² (+7.6%)	204.4 kWh/m ²	245.89 kWh/m ² (+20.3%)

Thermal Comfort: Operative Temperature (°C)	25.06 (+0.24%)	25.00	25.23 +0.92%
Thermal Comfort: Operative Discomfort Hours per Year	341.47 hrs (+21.1%)	281.92 hrs	387.17 hrs (+37.4%)
Thermal Comfort: Fanger PPD (%)	16.45% (+2.6%)	16.04%	17.03% (+6.2%)

5. Results and Conclusions

The simulation results provide a comparative analysis of energy consumption and thermal comfort across the three building prototypes: **courtyard**, **L-shape**, and **linear**.

- **Energy Performance:**
 The **linear prototype** illustrated the **lowest total energy use**, recording **251.97 kWh/m²/year**, while the **L-shape prototype** had the highest, reaching **295.78 kWh/m²/year**—a **17.4% increase** compared to the I-shape. The **Courtyard form** fell between the two, with **266.44 kWh/m²/year**, representing a **5.7% increase** over the **linear** shape.
- **Cooling Loads:**
 The **linear** shape again showed better performance, with a cooling load of **488,102.79 kWh/year**. The courtyard form had a **6.9% higher** load, and **L-shape** showed the least efficiency, with a **21.9% increase** in cooling demand over the Liner shape.
- **HVAC Energy Use per Unit Area** followed a similar trend:
 - **Linear shape: 204.4 kWh/m²**
 - **Courtyard: 219.9 kWh/m² (+7.6%)**
 - **L-shape: 245.89 kWh/m² (+20.3%)**
- **Thermal Comfort – Operative Temperature** remained relatively consistent across all models, ranging between **25.00°C and 25.23°C**, with only minor variations.
- **Discomfort Hours and Fanger PPD values** highlighted the Liner shape's thermal efficiency:
 - Liner shape had the **fewest discomfort hours (281.92 hrs/year)**, while the L-prototype had **387.17 hrs/year**—a **37.4% increase**.
 - Fanger PPD values remained below the 20% threshold for all models, with Liner shape at **16.04%**, courtyard at **16.45% (+2.6%)**, and L-shape at **17.03% (+6.2%)**.

6. Recommendations

Based on the simulation results, the following recommendations aim to guide the design and adaptation of school buildings in hot arid climates. They illustrate energy efficiency, thermal comfort, and the integration of passive strategies for sustainable educational environments.

• Adoption of Linear Shape Designs for New Schools

The **Linear shape prototype** demonstrated the best overall performance, achieving the lowest total energy use, cooling loads, HVAC energy per unit area, and discomfort hours. It should be prioritized for **new educational buildings** in climates similar to the study area.

• Improvement of Courtyard Forms with Passive Strategies

The courtyard prototype performed moderately but showed higher cooling demand. It can be improved through **passive ventilation enhancements, strategic shading, and reflective materials** to reduce heat gain.

• Retrofitting L-shape for Adaptation

Despite higher energy consumption, the **L-shape prototype** indicating potential for **thermal comfort improvement**. With retrofitting, such as **adding insulation, façade shading, and efficient HVAC systems**, the L-shape can be adapted effectively, making them more sustainable and a viable option for existing buildings.

• Integration of Passive and Climate-Responsive Measures

Across all prototypes, **natural ventilation, optimized orientation, and solar control strategies** are essential to further enhance comfort while reducing mechanical cooling needs.

• Using Simulation in Early Design Stages

Future school buildings should use simulation early in the design process to help create schools that balance energy efficiency with the well-being and comfort of their students and teachers.

Finally, in order to strengthen the environmental performance of future prototypes, school design should be approached holistically, within, integrating geometrical considerations with construction materials, orientation, and adaptive ventilation techniques. These elements interact dynamically, influencing how energy is distributed and perceived within the learning environment. Additionally, user behavior and daily operational patterns can play a measurable role in thermal performance. Integrating these connected design aspects into the early planning process can create learning environments that are not only energy-efficient but also more adaptive, comfortable, and genuinely centered around the well-being of students and teachers in hot-arid settings.

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