Courtyard Housing in Midrise Building

An Environmental Assessment in Hot-Arid Climate

By

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Abstract

This study is an evaluation of the environmental impacts of courtyard integration in midrise housing in the hot-arid climate of Dubai, The United Arab Emirates. A computer simulation (IES 6.0) is utilized to measure selected parameters: thermal analysis, solar shading, daylighting and airflow patterns, and primarily to determine the overall energy reduction.

This study is carried out in three steps: The first step, a comparison of conventional and courtyard models is carried out in six-storey buildings. The second step, a courtyard building is studied to determine design optimum parameters in which one variable changes at a time when all other remain constant according to a suggested prototype model (reference model), and the third step compares it again to the conventional model.

The first step concludes a reduction of 6.9% energy for the courtyard model. The second step concludes that the optimum design parameters for a courtyard model is achieved with ten-storey height, triple-glazed opening, 40 cm-thick wall and 10-cm thick Cellular Polyurethane insulation material. The third step achieves 11.16% total energy use reduction for six-storey courtyard model with the optimum parameters.

Finally, the study suggests guidelines and recommendations for efficient courtyard designs for midrise buildings. Furthermore, it extends recommendations of configurations to other different climates, besides the hot arid, in order to overcome the limitations of the proposed model.

Dedication

This work is dedicated To Lina and Maya.

Acknowledgements

While I was working on this dissertation, I have kept dreaming of that moment when I would get to this part, when I would look back at this period of my life with pleasure and gratitude.

I would like to thank God for giving me the inspiration and power in every thing I do.

Dr. Bassam Abu-Hijleh, my supervisor, thank you for your invaluable support, critique and patience during my study.

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My father and mother, thank you for always being there for me.

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Finally, Lina and especially Maya, my little one who was born before this dissertation was completed, thank you for being my “biggest” supporters!

Table of Contents

List of Figures

List of Tables

Nomenclature

ACH	Air changes per hour
Altitude	A solar angle indicates the sun height in the sky
AR	Aspect Ratio
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CE	Carbon emission
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power System
clo	A unit of thermal resistance describes insulating value of clothing
CO_2	Carbon dioxide
Conductivity	Heat transfer through direct contact within or between two surfaces with different temperature
DBT	Dry Bulb Temperature
DF	Daylight Factor; expressed as [%]
Diversity	The ratio between the minimum illuminance on a working plane within a room and the maximum illuminance
DOE	U. S. Department of Energy
EF	Ecological Footprint
Emissivity	Ability of a material surface to emit energy by radiation
GDP	Gross Domestic Product: a measure of a country's economic output
gh	Global hectare: a measurement of biocapacity of the entire earth
HVAC	Heating, ventilating, and Air-conditioning system
IEA	International Energy Agency
IES	Integrated Environmental Solutions Software
Illuminance	Light density on surface, expressed as [lux: lumens per unit area]
Latitude	Location of a place on Earth north or south of the equator

Longitude	geographic coordinate of a place for east-west measurements
lux	Unit of illuminance; lumens per square meter
met	level of the activity equals the minutes needed to expend 150 kcal
MWh	Megawatt hour; a unit of energy
Pa	The pascal; a unit of pressure measurement
PV	Photovoltaic panel
Reflectivity	Redirection of incident radiation of a material
SSI	Solar Shadow Index
Surface to Volume Ratio	Amount of surface area per unit volume of an object
Thermal Mass	Material has high thermal capacity [ability to store heat]
Time lag	The time delay due to the thermal mass
Transmittance	The fraction of incident light at a specified wavelength that passes through a sample
U Value	Coefficient of heat transfer; expressed as [W/m² K]
Uniformity	The ratio between the minimum illuminance on a working plane within a room and the average illuminance
USGBC	US Green Building Council
VE	Virtual Environments Software
λ Value	Rate of heat flow through a volume with temperature difference between the two sides; expressed as [W/m °C]

Chapter 1: Introduction

1.1. The World Sustainability Scenario

We are facing a big challenge: our ecosystems cannot sustain the current levels of economic behavior and material consumption. The average person creates an ecological footprint (EF) several times larger than what the earth can sustain according to a report published by Living Planet (2006, p. 30). The Ecological Footprint is a measure of the demand that human puts on the planet, thus estimating the amount of biologically productive land and water area required to produce all the resources an that individual, population, or activity consumes.

Several sectors are major contributors to EF among which are: electricity, transportation, industry and building construction, as reported by the International Energy Agency (IEA 2007). The International Energy Agency further draws a significant impact generated by the residential building industry as well as the electricity demand with regard to the total carbon dioxide emissions (Figs. 1 and 2).

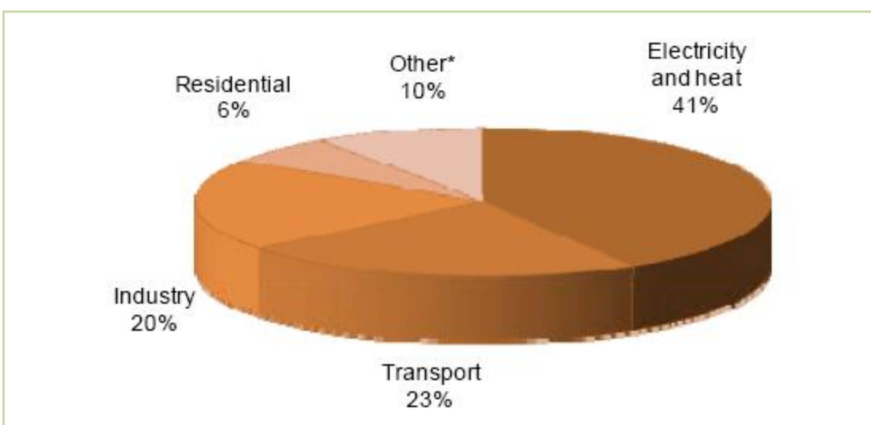


Figure 1. World CO2 emission by sector (IEA 2007)

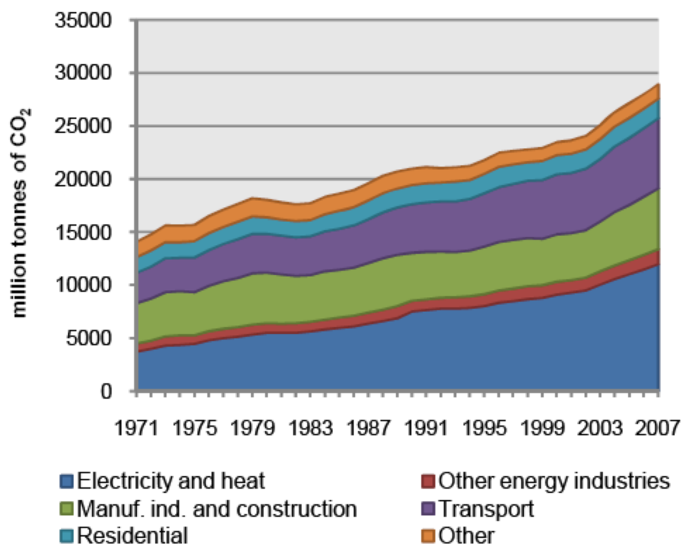


Figure 2. CO2 Emission by sector (IEA 2007)

Furthermore, the US Green Building Council (USGBC 2008) reports that the building industry in developing countries constitutes a very important contributor to the overall ecological footprint. According to USGBC statistics, residential buildings account for a massive 40% of the total carbon dioxide emissions, 40% of all energy usage, 68% of electricity utilization, 10% clean water consumption and 50% of non-industrial waste generation.

Architects bear an important responsibility toward the built environment by adhering to social, cultural and climatic identities and are therefore able to achieve a significant footprint reduction without compromising quality of life. Furthermore, architects can learn from history where the built environment was a sustainable response and a natural reflection of the society, culture and climate, thus causing less destruction to natural resources.

1.2. The UAE Sustainability Scenario

The United Arab Emirates is one of the fastest growing urban countries in the Middle East and this brings both opportunities and responsibilities. Dubai and Abu Dhabi resemble the construction fabrics for metropolitan cityscape and is compared in many areas to New York City, London and Paris. Particularly in Dubai, the construction industry has flourished in recent years with hundreds of new buildings added annually (Fig. 3). This growth has been extremely fast lately causing environmental issues such as increased pollution, increased energy consumption, reduced natural resources, compromised air quality, and increased human health concerns and consequently deteriorating the overall environmental ecosystem.

Figure 3. Dubai Construction Scenario- Sheikh Zayed Road (Personal Archive)

According to the Living Planet Report (2006), the ecological footprint (EF) per person in the UAE is estimated 11.9 global hectares (pp. 15 & 30), which is six times higher than the world average bio-capacity per person, and 14 times higher than the carrying capacity per person which is only 0.8 global hectare. The water withdrawal in the UAE is 1533% of total resources. The highest portion of the ecological footprint per person is from the CO2 emissions from fossil fuel, this CO2 footprint was the fastest growing component, and it can be emitted into atmosphere faster than it is removed or absorbed by the ecosystems within the country's own borders. The Ecological Footprint of Nations 2005 Update states that the total EF of a UAE person is 232.86, while the biological capacity is 19.43, with negative balance equals to -213.43. Figure 4 shows also that UAE is among the top countries in terms of the CO2 emissions with relation to the Income per Person indicator (GDP per capita).

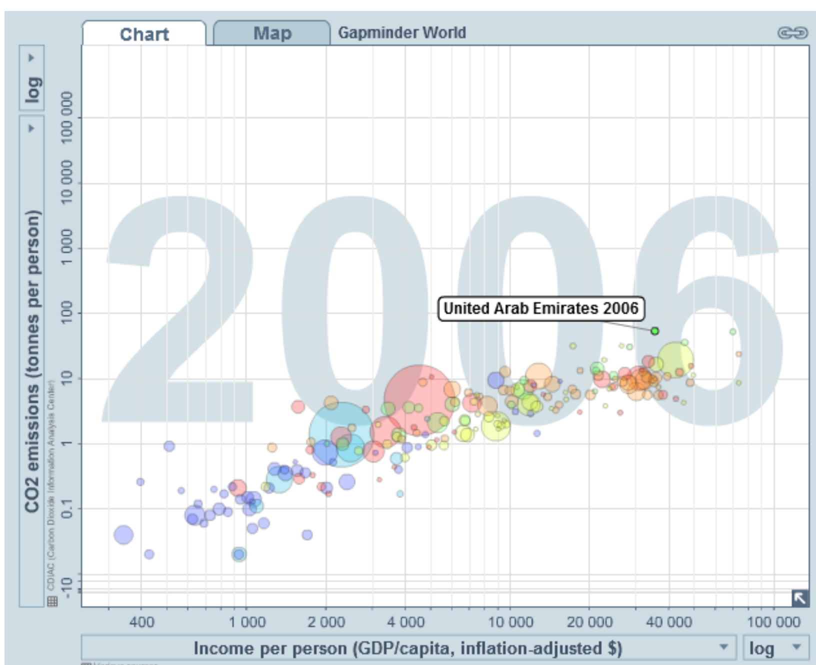


Figure 4. CO2 emissions with relation to the Income per Person indicator (http://graphs.gapminder.org/)

Another critical factor to the above is that the UAE population is growing much faster than any other nation and thus the CO2 emission could further increase in the coming years. This rapid growth in population is creating ecological imbalance as well as adding more threats to human survival. The UAE population reached 7.5 million in 2010 compared to the earlier figure of 5.630 million in 2006 as published by The National Human Resources and Development and Employment Authority, Tanmia (2009). Tanmia further expects the UAE population to double every 8.7 years, which is much faster than the 55-year global estimated average.

The population growth has added more pressures on the housing sector, and thus substantially increased energy demands. Selections made in the housing sectors, such as typologies and materials, contribute radically to the energy consumption. For example, the contemporary models of housing with large glass facades are a more desired choice today in the building construction in the UAE, and yet considerably contribute to the heat built-up inside buildings which further leads to increased air conditioning requirements.

All of the above raise the need to apply protective measures such as green buildings and more environmentally considerate life style. The green building initiative is not a luxury but simply a much-needed response to deteriorating natural resources and the risks associated with the rapid increase in the building industry. Additionally, the public can be engaged in making choices that reduces environmental risks, increases sustainability, and still satisfies the inhabitance and existence for generations ahead.

Chapter 2: Literature Review

2.1. History of Courtyard Houses

Courtyard form is as old as the man dwelling on earth. Some of the oldest courtyard houses are found in the oldest civilizations of Iran as well as China, and dates back to 3000 BC (Edwards 2006). The courtyard in the house is the center of interest and has historically been used for many purposes including cooking, working, playing, gathering, and even sleeping during the hot summer nights.

One type of historical courtyard houses is found in Chinese culture where houses were constructed with multiple courtyards to provide privacy and harmony. Strangers were received in the outermost courtyard, while the innermost ones were reserved for close family members. These forms were imported to the Middle East for example the Manah in Oman, Fig. 5.

Figure 5. A view of the old fabric in Manah, Oman (Edwards 2006)

"Before courtyards, open fires were kept burning in a central place within a home, with only a small hole in the ceiling overhead to allow smoke to escape. Over time, these small openings were enlarged and eventually led to the development of the centralized open courtyard we know today. Courtyard homes have been designed and built throughout the world with many variations in every century" (Wikipedia 2009).

The courtyard houses were found in all variations of space, time and climate. However, they are perhaps more common in hot and warm climates, as in the Middle East and the tropical regions, as an open central court can bring important cooling effects for the house, and allow for other benefits needed in the human dwelling such as breeze, daylight, privacy and security. Courtyard houses in the Middle East include rooms for cooking, sleeping that are shared by several family siblings and often have flat rooftops to safeguard against high temperatures in the summer while offering cool breeze at night within the private space of own family. Moreover, in Islamic culture, courtyards provide private space for females to relax while unobserved. Fathy (1973) states that "... to the Arab especially, the courtyard is more than just an architectural device for obtaining privacy and protection. It is, like the dome, part of a microcosm that parallels the order of the universe itself".

2.2. Social and Cultural Dimensions

In the Arab regions, "privacy is a fundamental need in housing. The courtyard is the women's domain and it must be kept from the public eye" (Reynolds 2002, p. 48). This explains the introverted nature of the space, as all the rooms are open to a central courtyard, whereas the external envelop is solid with minimal openings, Fig. 6. The solid doors and grilles on the external facades control privacy and interaction with the public domain. The space configuration secures privacy through the location of the entry and opening points. One example shown in Fig. 7 is to shift the entrance from the courtyard axis to prevent direct sight of the interiors.

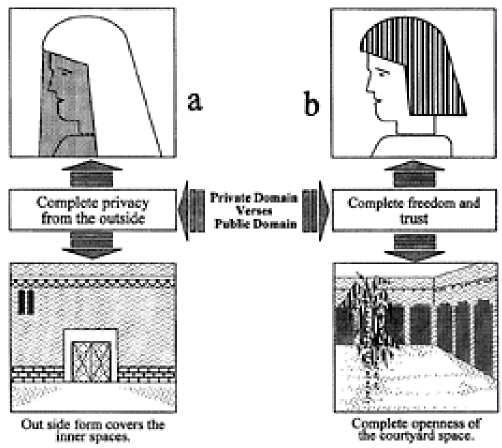


Figure 6. Private domain (courtyard) vs. public domain (outside). (Edwards 2006)

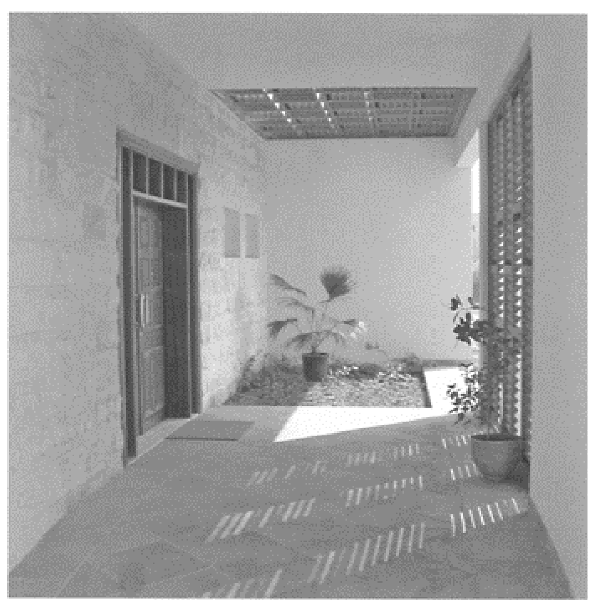


Figure 7. Entrance location shifted to provide internal privacy (Edwards 2006)

Edwards (2006, p. 227) draws an analogy between the sheltering layers of the courtyard houses and the costumes worn by their occupants. Both are made of layers and emphasize the need for protection. This shared principle is a reflection of the harmony that exists between the culture and the objective knowledge as a built environment.

Figure 8 shows a form of multiple houses sharing a common and large courtyard; this form loses the privacy and becomes simply an extension of the public space.

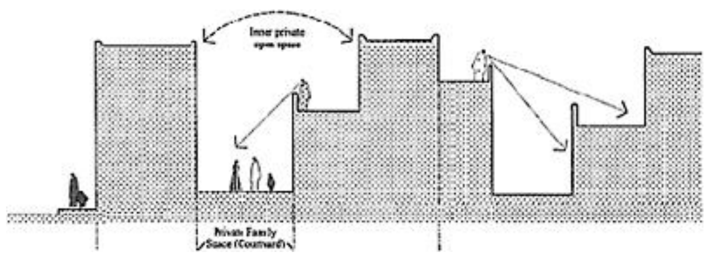


Figure 8. A section through adjoining houses shows the lack of privacy (Edwards 2006)

2.3. Forms and Geometries

2.3.1. Shape

In the fabrics of old cities, the shape of a courtyard is usually square or rectangular. The irregularity of the plot is due to the configuration of the streets and alleys outside and is usually accommodated by the rooms' perimeters, Fig. 9. (Fathy 1982, p. 68, cited in Reynolds 2002, p. 9)

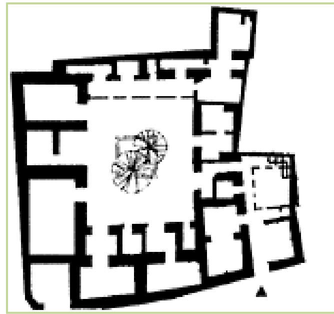


Figure 9. Irregularity of shape due to streets configurations (Edwards 2006)

Other shapes such as circular may have occasionally existed in the vernacular structures in old societies, such as Somba village in Africa (Fig. 10). The compact urban fabric protects the houses agianst the wind and sand storms, and reduces the heat gain through less external surfaces and walls (Hyde 2008, p. 173).

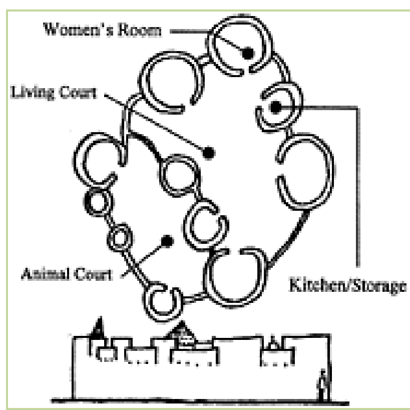


Figure 10. Samba Village in Africa (Edwards 2006)

It is observed that in hot arid climates, the urban fabric is dense and tight compared to the warm humid climates, where the urban fabric becomes spaced and open to enhance air movement between buildings, Fig. 11.

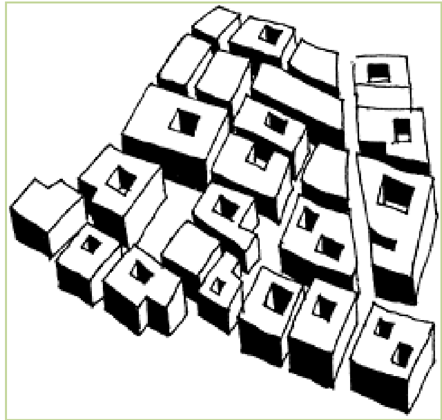


Figure 11. Compact and tight fabric in the hot arid climate (Edwards 2006)

2.3.2. Parameters: Length, Width and Height

The climatic properties of a courtyard and the surrounding rooms depend on their proportions. Figure 12 shows a recommended courtyard width, which ranges from x to 3x, where x is the coutyard height (Koch-Nielsen 2002, p. 57).

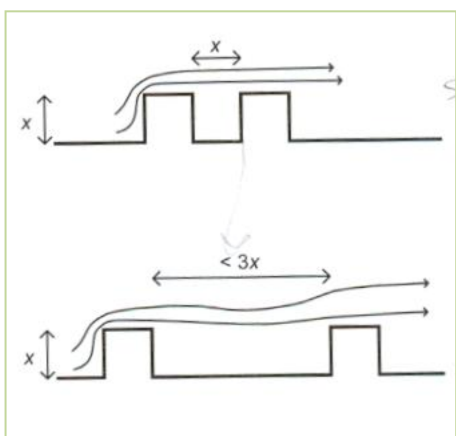


Figure 12. Width of courtyard in relation to its height (Koch-Nielsen 2002)

However, the vertically deep courtyard is recommended to enhance the daytime internal shading, where as a wider courtyard would enhance the ventilation across the house (Hyde 2008, pp. 327 & 331).

According to Laffah, the most common proportions of width to length ratios are: 1:1.8 and 1:3.6, which depend essentially on the sunpath (cited in Edwards et al 2006, p. 149). Another factor is the ratio of the built area to the courtyard area, which is according to Wadah (2006, p. 156) should range from 1.5 to 2.7, otherwise the courtyrad will be too small or too large to be environmentally effective. On the other hand, Reynold (2002, p. 177) suggests that at least 25% of the plot to be open to the sky.

Reynolds further defines two parametric factors that deal with the courtyard exposure (Figs. 13 and 14):

1. Aspect Ratio (AR) is defined as "the degree of openess to sky". Therefore, the greater the aspect ratio, the more exposed the courtyard is to the sky. This factor is considered when designing the house for the daylight, and is calculated as follows (2002, p. 16):

$$\boldsymbol{Aspect\ Ratio} = \frac{\boldsymbol{area\ of\ courtyard's\ floor}\ \ (\boldsymbol{m^2})}{(\boldsymbol{average\ height\ of\ walls})^2\ (\boldsymbol{m})} \qquad (1)$$

2. The Solar Shadow Index (SSI) is another factor described by Reynolds (2002, p. 17) which deals with winter sun exposure. The greater the solar shadow index, the deeper the wall formed by the courtyard and thus the less winter sun reaches the floor or the south wall.

$$\boldsymbol{Solar\ Shadow\ Index} = \frac{\boldsymbol{south\ wall\ height}\ (\boldsymbol{m})}{\boldsymbol{north{-}south\ floor\ width}\ (\boldsymbol{m})} \qquad (2)$$

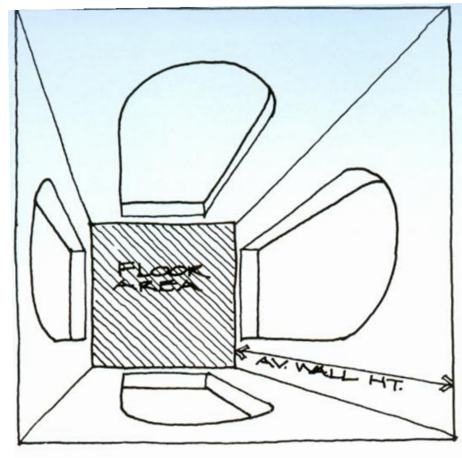


Figure 13. Aspect Ratio (Reynold 2002)

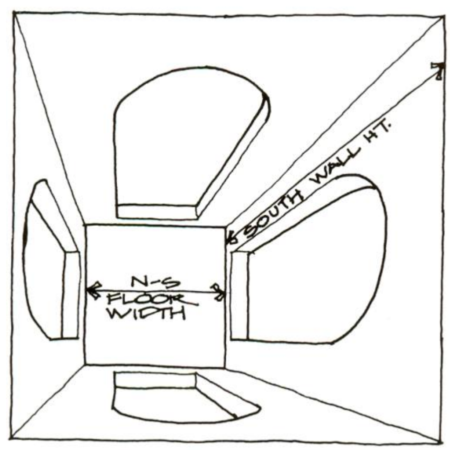


Figure 14. Solar Shadow Index (Reynold 2002)

Consequently, if the courtyard is wide and shallow (high aspect ratio), it performs as sun collector. On the other hand, the narrow and deep courtyrad (low aspect ratio) performs as a sun protector, in which orientation has a weak effect on the house.

2.3.3. Modern Courtyard Forms in Multi-family Dwellings

Hakmi (2006) attempted to evolve the concept of the courtyard into the modern housing fabric, in order to achieve a better response to the local climate and cultural needs. He examined the performance of single- and multi-family dwelling using analytical methods to define the difficulties and potential of such proposals. Furthermore, he tested many possible alternative configurations against social, climate, privacy and daylight considerations (Hakmi 2006, cited in Edwards et al 2006, p. 187). Different possible layouts were proposed for single-family courtyard dwellings of one or two-storey along with some examples (Fig. 15).

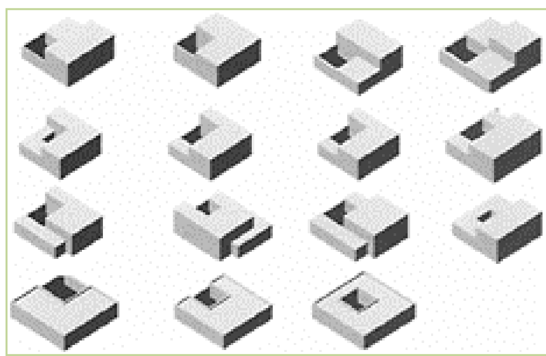


Figure 15. Possible layouts for single-family courtyard dwellings (Hakmi 2006)

On the other hand, Hakmi stated that the multi-storey dwelling is predominant in our modern urban setting due to economic and cultural changes (2006, pp. 190 &191). Therefore, he proposed possible alternatives of courtyard houses into a modern context. The main characteristics of these proposals are:

- The courtyard constitutes 16-30% of the plot size
- The houses areas range from 100 m² to 250 m²

- The courtyard plays a fundamental role in daylighting in addition to its social and aesthetics roles, the day and night zones are separated functionally accordingly
- Main circulation takes place through the covered area, as opposed to the traditional courtyard house, where all movement takes place across the courtyard
- The configuration of these alternatives assures complete privacy for their residents

The suggested alternatives contain five different types as starting points in which it can be modified in the future in order to adapt to the applicable climate and culture. These types are classified according to their dimensions, height (number of floors), number of dwelling units per block, number of types and the unit type as being one or two levels (Hakmi 2006, pp. 193- 201). Figures 16 and 17 show examples of these proposals.

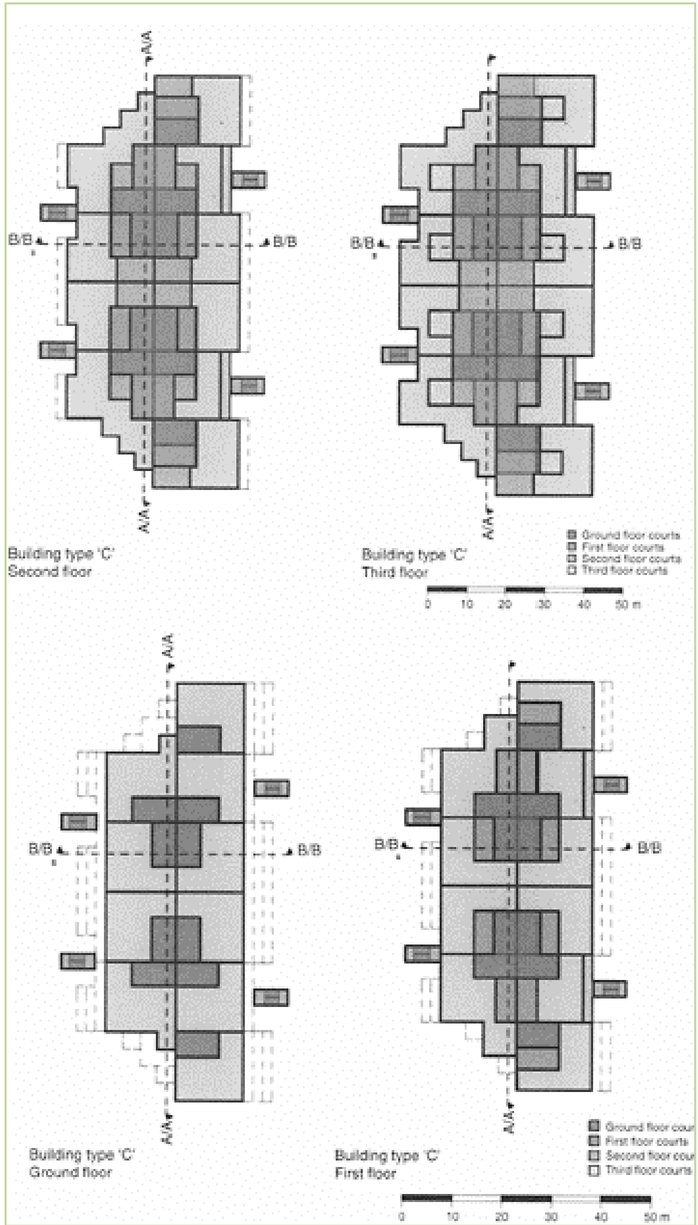


Figure 16. One of the suggested midrise courtyard housing types: plans at ground, first, second and third floors (Hakmi 2006)

In conclusion, Hakmi stated that:

- It is possible to invent a modern housing urban fabric derived from the traditional courtyard

- The European urban systems for single family dwelling (setbacks house) do not represent a proper base for the courtyard housing type
- Plots with dimensions of 12 x 12 m to 14 x 14 m represent the optimum size for adopting the courtyard housing types in single- and multi-family unit dwellings
- The courtyard, surrounded by closed spaces on at least three sides, allows for adequate ventilation and daylight

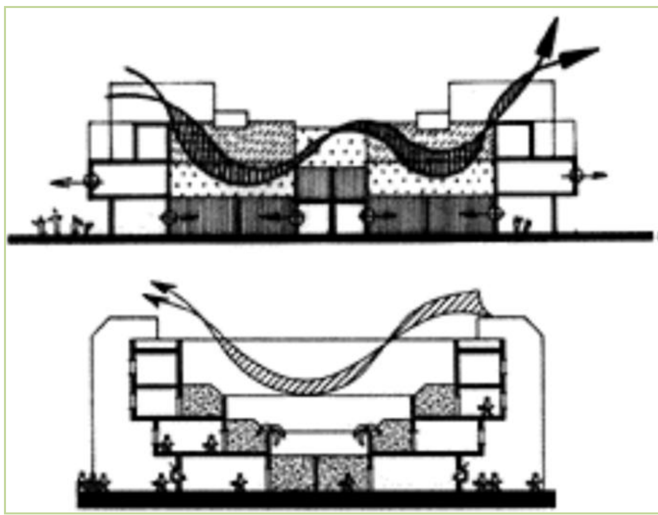


Figure 17. Possible rearrangement of cross-sections to provide compact courtyard housing (Hakmi 2006)

2.4. Thermal Analysis Studies

The courtyard in the house acts as a buffer zone and thermal mediator between the outdoor and indoor. Additionally, the thermal control in the courtyard house can be further achieved by employing many strategies such as thermal mass utilization, high surface area to volume ratio and proper selection of materials.

In hot climates, the Thermal Mass (thick perimeter walls) can be cooled through radiation during the night. The thermal mass is slow to increase in temperature as air temperature rises, and slow to cool as air temperature falls (Reynolds 2002, p. 92). This means that the interior temperature lags several hours behind the exterior temperature.

Surface Area to Volume Ratio is an indication of the rate at which the building heats up during the day and cools down at night (Koch-Nielsen 2002, p. 46). This ratio is obtained by dividing the total surface of the building including facades and roofs by their volume. A higher ratio leads to a higher heat gain during the summer and heat loss during the winter. Additionally, a high ratio provides an increase in the potential ventilation and daylighting, which may offset the disadvantage of the larger surface area (Raydan et al 2006, p. 141, 142)

The selection of materials has a great influence on the heat entry control into the house, with regard to their thermal properties like reflectivity, emissivity and absorptivity. Thus, the external surfaces (roofs and walls) with high reflectivity reduce the heat gain, whereas the high emissivity ones release the heat gain at night.

On the thermal performance of the courtyard, a study by Aldawoud (2007) was carried out to assess the energy reduction under different factors:

- Climate: hot-dry, hot-humid, temperate and cold climates
- Height: from 1 to 10 floors
- Glazing type and glazing percentage: 4 different types with 4 different percentages

An energy program of DOE 2.1E was used for the model energy simulation. The model was simplified to have only the courtyard and four adjacent zones, Fig. 18.

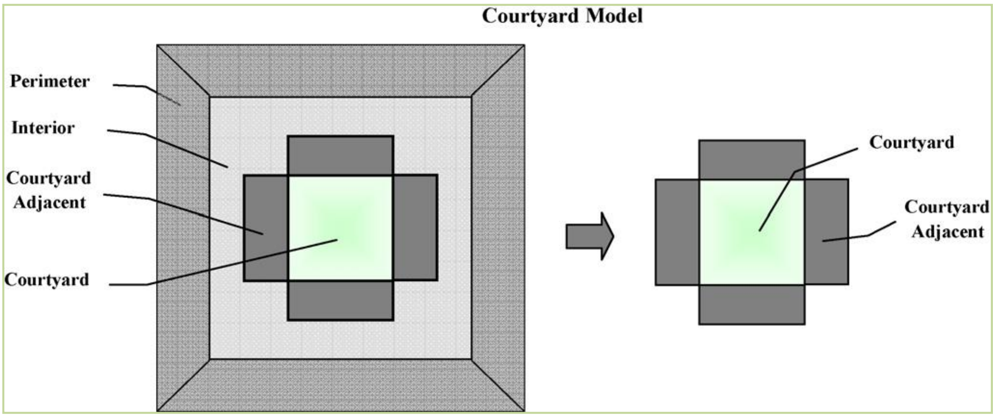


Figure 18. The Study model: Perimeter and interior zones are excluded from the model (Aldawoud 2007)

The major findings of this analysis were that the courtyard integration in all climates was an energy efficient option. Nevertheless, the hot arid and hot humid climates show a significant increase in energy reduction compared to the temperate in cold climates. It was also found that the type and percentage of glazing affects greatly the energy performance of the courtyard. For example, in a courtyard with double clear glass, the total energy consumption was lowered by 24% compared to a courtyard with single clear glass, with a glazing percentage of 30%. Furthermore, the reduction reached 43% with the use of triple clear glass, as per the study calculations.

However, courtyard efficiency depends on many variables and its integration is relevant to all climates. This integration was most evident in the hot dry and hot humid climates, Table 1.

Table 1. Climatic comparison of double clear glass thermal performance based on energy consumption in cold climate at 10 floors (Aldawoud 2007)

Glazing type	Energy consumption	Reduction in energy consumption (%)
Cold climate (Minneapolis)	1433.888	
Temperate climate (Chicago)	1138.028	−21
Hot-dry climate (Phoenix)	1097.95	−23
Hot-humid climate (Miami)	974.739	−32

The energy performance in a central atrium, according to Aldawoud and Clark (2007), was compared with the similar geometry of a courtyard in four climatic regions: cold, moderate, hot humid and hot dry. The paper assumed that the atrium and the courtyard share the same function and both act as a central space, light enhancing tool and direct link to the outdoor environment. In spite of that, they behave thermally in a completely different manner. The investigation was carried out through two computer models created in DOE2.1E to calculate the heating and cooling loads. Both represented office buildings with the same geometrical proportions. The variables investigated in this study were height and glazing type, similar to their previous study.

It was concluded that:

- It is recommended to have low U-value glazing types and lower glazing percentage.
- The energy reduction was optimum when using triple clear glass, which can reach up to 43% compared to a courtyard having single clear glass.

- Increasing glazing percentages resulted in energy inclination in the courtyard model in all climates, while the atrium showed better energy performance under this condition compared to the courtyard.
- The courtyard was found an energy efficient option in all climates. However, it was mostly optimum performer in the low and mid-rise buildings, while the atrium was the energy efficient option for high-rise buildings.

Figure 19 shows the building with the lowest annual energy consumption for the number of floors and the glazing types and percentages, where the blue indicates the courtyard model and the red indicates the atrium model. The other climatic regions were excluded as being outside the focus of this study. The graph shows that the courtyard in hot dry climates, with single clear glass and 30% glazing, was more energy efficient up to ten floors compared to the atrium having a skylight with 80% single clear glazing. The atrium performed better in heights above ten floors. This conclusion will draw a base for this research proposal.

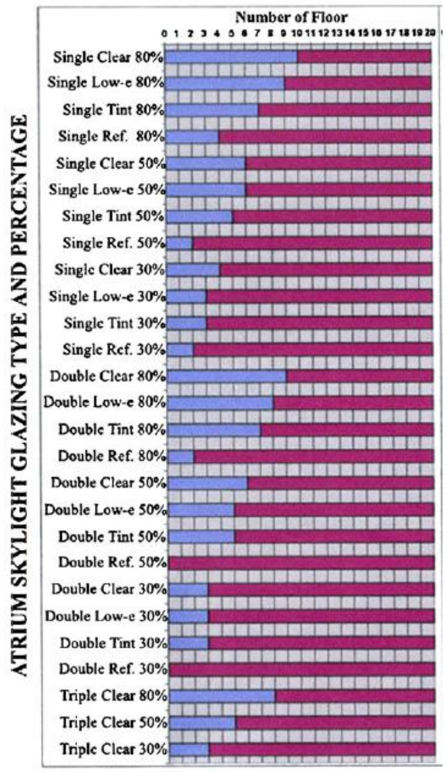


Figure 19. Graph indicates the building from exhibiting the lower annual energy consumption for the number of floors and various atrium skylight glazing types and percentages, compared with courtyard having 30% single clear glass (Aldawoud 2007)

2.5. Shading and Daylight Studies

Muhaisen (2006) carried out a study using computer simulation on the effect of the rectangular courtyard proprtions on the shading and exposure conditions in four different climates, using two ratios, R1 and R2, to obtain an optimum wall-shaded area in summer and at the same time optimum sun-lit area in winter, Table 2. These ratios were defined as follows:

$$R1 = \frac{\boldsymbol{floor\ area}\ (\boldsymbol{m^2})}{\boldsymbol{height}\ (\boldsymbol{m})} \quad (1\ to\ 10) \qquad (3)$$

$$R2 = \frac{\boldsymbol{width}\ (\boldsymbol{m})}{\boldsymbol{length}\ (\boldsymbol{m})} \quad (0.1\ to\ 1) \qquad (4)$$

Table 2. Optimum ratios and their corresponding maximum wall shaded and sunlit areas (Muhaisen 2005)

Location	Summer		Winter		Acceptable reduction	
	Optimum ratio	Maximum value (%)	Optimum ratio	Maximum value (%)	Summer (%)	Winter (%)
Kuala Lumpur	$R_1 = 1$, $R_2 = 0.1$	95.3	$R_1 = 10$, $R_2 = 1$	44	40	40
Cairo	$R_1 = 1$, $R_2 = 1$	82.6	$R_1 = 10$, $R_2 = 1$	37.5	35	50
Rome	$R_1 = 1$, $R_2 = 0.1$	92.4	$R_1 = 10$, $R_2 = 1$	30.8	40	40
Stockholm	$R_1 = 1$, $R_2 = 0.1$	96.7	$R_1 = 10$, $R_2 = 1$	5.6	50	40

Muhaisen (2005) recommended narrow forms of courtyard in the hot arid climate. The study also examined the effect of height on the annual energy performance of the courtyard in the examined locations as in Fig. 20. Muhaisen stated that the higher the courtyard the deeper it is and thus the more shading it provides. In hot climates, the courtyards tend to be deeper to provide more shadow and less solar gain, whereas in the cold climates the courtyard is shallower to allow solar heat gain into the house.

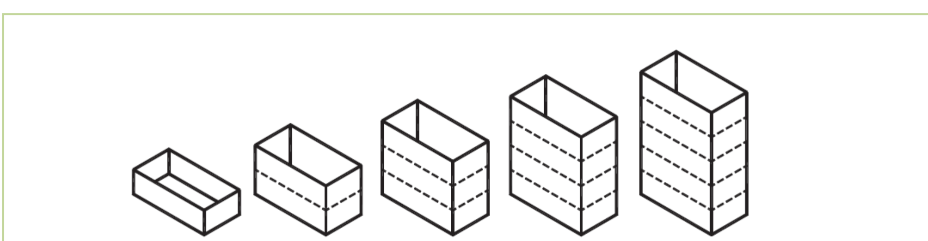


Figure 20. Investigated heights of the courtyard buildings (Muhaisen 2005)

Additionally, a rectangular courtyard with R2 of 0.5 and a height of one storey (3 meters) was taken as a reference model for testing the effect of the variable heights (number of storeys) on shading conditions. Furthermore, different heights from one- to five-storey were tested against the base model with regard to the percentage of shaded and exposed areas in summer and winter respectively. However, the results showed that the increase in number of storeys leads to an increase in the shaded area in summer. On the other hand, it showed that the higher the sun altitude is the less is the sensitivity of the shaded area's response to the height increase, as in Cairo, Table 3. Table 4 shows the reductions in the maximum shaded and exposed areas at the examined heights in the four locations.

Table 3. Average rate of increasing the shaded area and decreasing the exposed area due to increasing height by one storey (Muhaisen 2005)

Kuala Lumpur		Cairo		Rome		Stockholm	
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
4.3%	−6%	2.5%	−7.5%	3.4%	−6.6%	6.3%	−1.3%

Table 4. Reduction percentage in the maximum achievable shaded and sunlit areas (Muhaisen 2005)

Building height	Kuala Lumpur		Cairo		Rome		Stockholm	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
One storey	17	0	10	0	14	0	25	0
Two-storey	14	5	8	14	11	16	19	3
Three-storey	10	11	6	23	7	22	13	4
Four-storey	6	18	3	27	4	25	6	5
Five-storey	0	24	0	30	0	26	0	5

Muhaisen (2005) concluded that in Cairo and Rome, the optimum performance in summer and winter can be achieved at the height of two storeys, whereas a three-storey courtyard performs efficiently in Kuala Lampur. In Stockholm, the most efficient height is one storey as the winter performance is the more critical.

In research papers for Muhaisen and Gadi (2005), a study was conducted to examine the effect of the multi-sided (polygonal), circular and rectangular geometries of the courtyard on the shaded and sunlit areas through computer calculations (IES Program), Figs. 21 and 22.

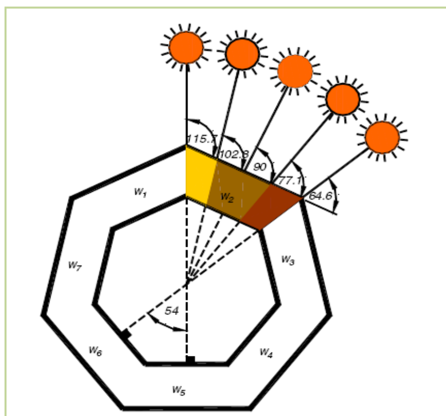


Figure 21. Polygonal courtyard (Muhaisen 2005)

It was found that deeper and more elongated courtyard forms are recommended to achieve maximum internal shaded area in summers, which accordingly resulted in less annual energy requirements. According to Muhaisen, this form enhanced the self-shading thus reduced the need for cooling by 4%.

The optimum ratios were defined as those which ensure minimum energy loads throughout the year assuming that the energy required for cooling and heating are dealt with equally. Courtyard with R1 equal to or greater than 5 was recommended throughout the whole year. However, he concluded that a geometrical shape has more influence in summer than in winter, Fig. 22.

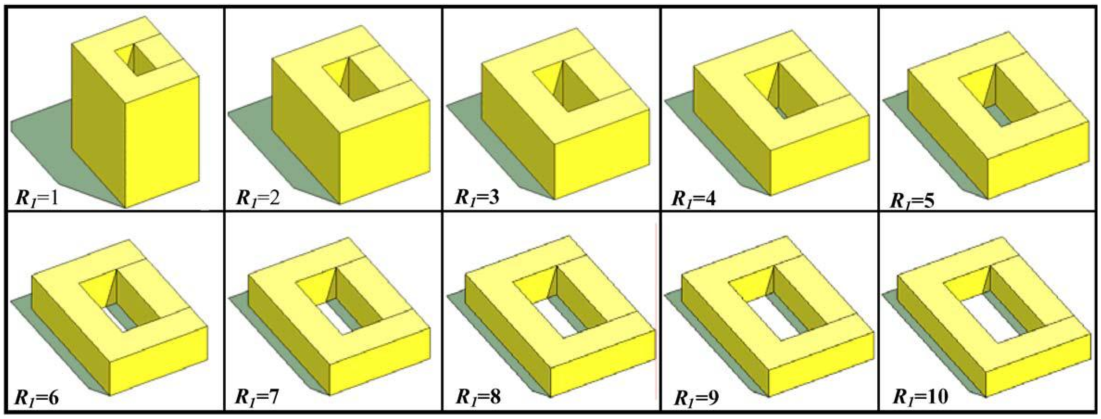


Figure 22. Examined courtyard forms with R2 of 0.5 and R1 ranging from 1 to 10 (Muhaisen 2005)

Another study by Meir, Pearlmutter and Etzion (1995) was undertaken on two courtyards in hot arid climates, identically shaped and similarly treated but differently oriented. These courtyards were part of a complex serving a high school. The height to width ratio (H/W) was in the range of 0.47 to 0.56, while the length to width ratio (L/W) was approximately 3.8. The courtyards were oriented to two different directions: south and west, Fig. 23. The air temperature and relative humidity were monitored for three days during one of the hot periods of summer and during the cold period of winter.

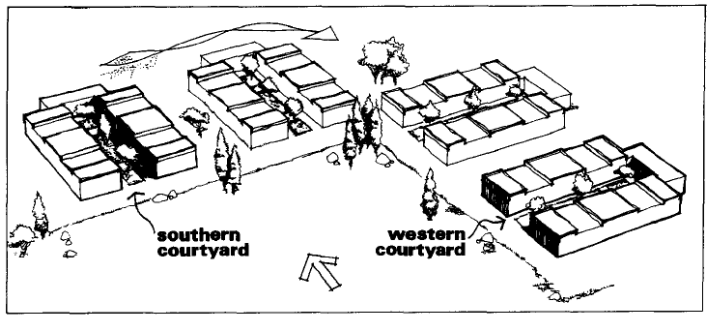


Figure 23. General layout of the monitored courtyards' area (Meir 1995)

The internal shading in summer was monitored for both courtyards, and it was found that the direct solar radiation reaches a considerably larger portion in the west-facing courtyard than in the south-facing courtyard during the early morning and late afternoon hours, which was a significant factor in the accelerated heat gain as shown in Fig. 24 and 25. In conclusion, the geometry and orientation of the courtyard spaces influenced their thermal behavior respectively. It was also observed that the courtyard spaces were overheated during daytime in the summer, irrespective of orientation, due to the inadequate ventilation and trapped radiation.

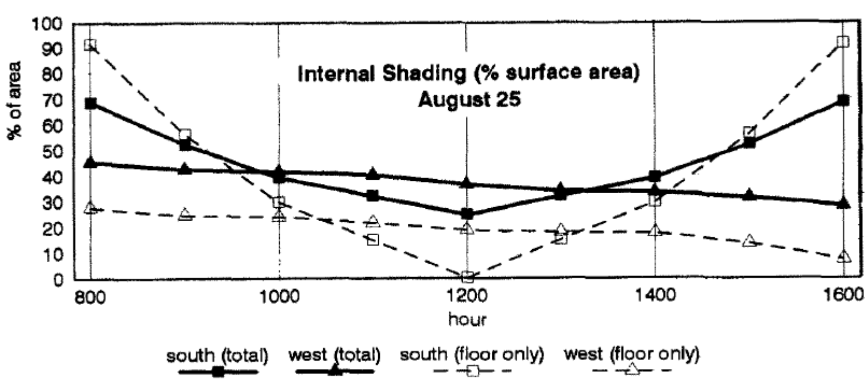


Figure 24. Internal shading of the courtyard for both directions (Meir 1995)

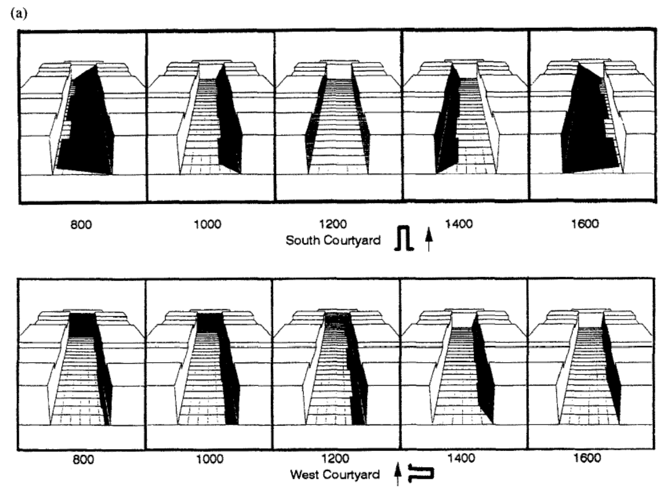


Figure 25. Percentage of total and floor surface areas in shade (Meir 1995)

2.6. Airflow and Ventilation Studies

The air movement into a building affects the thermal comfort of occupants and influences heat gain or loss through its envelope. Airflow and natural ventilation through buildings can be achieved in two ways:

- Temperature-generated pressure differences (stack effect): based on the fact that hot air rises and exits through the top opening, and cool air settles at the bottom.
- Wind-generated pressure differences (cross ventilation): where air travels from the openings across the space.

During the day, the courtyard heats up quickly, which enhances the stack effect due to high air temperature differences. However, this happens when outside temperature is cooler than inside. Kwok and Grondzik (2007,

p. 145) suggest that the temperature difference should be at least 1.7 °C for the stack effect ventilation. Nevertheless, another way to achieve higher stack effect performance is to increase the height.

The stack effect ventilation works better if the air passes by vegetation or water. On the other hand, it is recommended to have the openings at different heights with an area for the inlet and outlet not less that 3-5% of the floor area they serve (Koch-Nielsen 2002, p. 126). Another method to determine the inlet area with respect to the design wind speed is shown in Fig. 26.

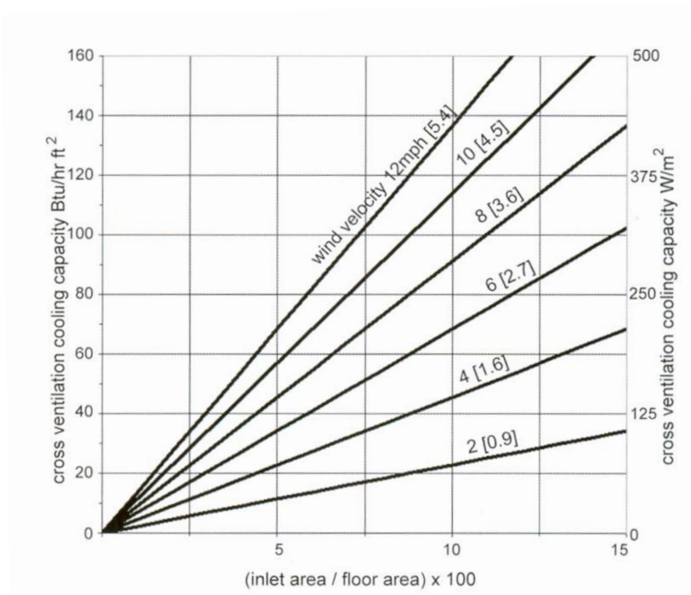


Figure 26. Inlet area with respect to wind speed and velocity (Koch-Nielsen 2002)

As for the cross ventilation during the night, the courtyard collects the cool air from the sky then passes it to the internal spaces, Fig. 27 (Koch-Nielsen 2002, p. 57).

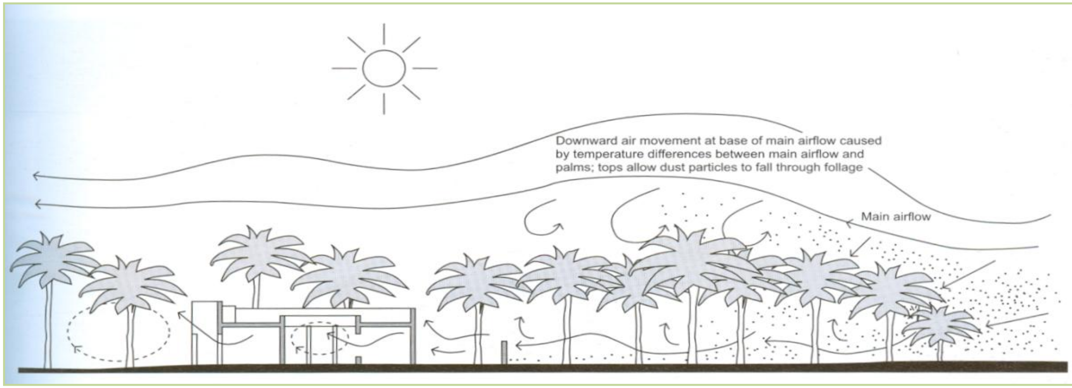


Figure 27. Cross ventilation (Koch-Nielsen 2002)

On the other hand, the slightly sloped roof design, oriented toward the prevailing wind, plays a considerable role in directing the cool air movement towards the courtyard during the night. However, it is recommended that the outlet opening is smaller in area than the inlet opening to enhance a greater pressure difference and draw the air inside the house.

An experiment by Al-Hemiddi and Al-Saud (2006) was conducted to assess the thermal performance of the internal courtyard in the hot-dry climate, and determine the impact of an evaporative cooling tower, as a stack ventilation method, on the thermal conditions of the courtyard and its surrounding rooms. Therefore, a mathematical model was created to calculate the airflow rate, air speed and indoor temperature in a single family, one-storey courtyard house as shown in Fig. 28. The outside windows cover 8% of the external wall area, whereas the inside windows cover 30% of the courtyard wall area.

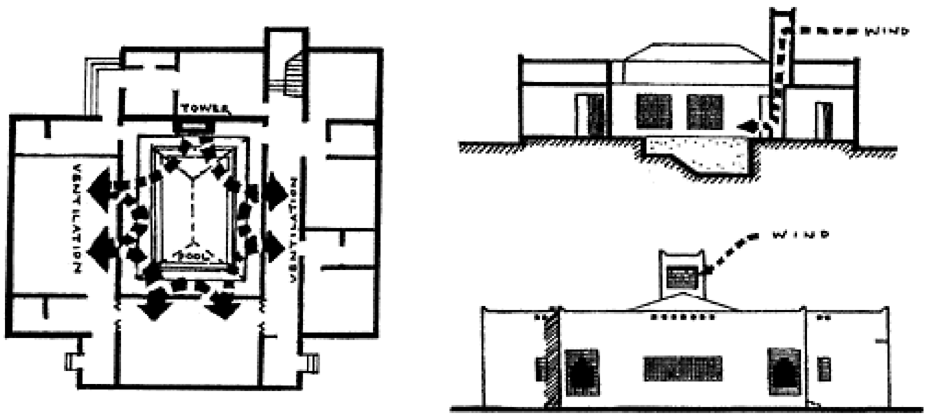


Figure 28. Plan and sections of the study house showing the role of the cooling tower in ventilating the courtyard (Al-Hemiddi and Al-Saud 2006)

The study was conducted in three phases:

- Cooling tower is off,
- Cooling tower is on,
- Cooling tower is working with the help of auxiliary fans.

Four weather data were monitored and analyzed: Dry bulb temperature, relative humidity, wind direction and speed and solar radiation.

In phase one, when the cooling tower was off, it was observed that the temperature in the courtyard is lower than the outdoor. The temperature reached the lowest in phase three, when the cooling tower with the fans were working. It was concluded that evaporative cooling tower contributes significantly in improving the thermal conditions within the courtyard and the surrounding living spaces as in Fig. 29. Moreover, the courtyard acts similar to a thermal sink that provides coolness in the hot arid climate (Al-Hemiddi and Al-Saud 2006, cited in Edwards et al 2006, pp. 163-170).

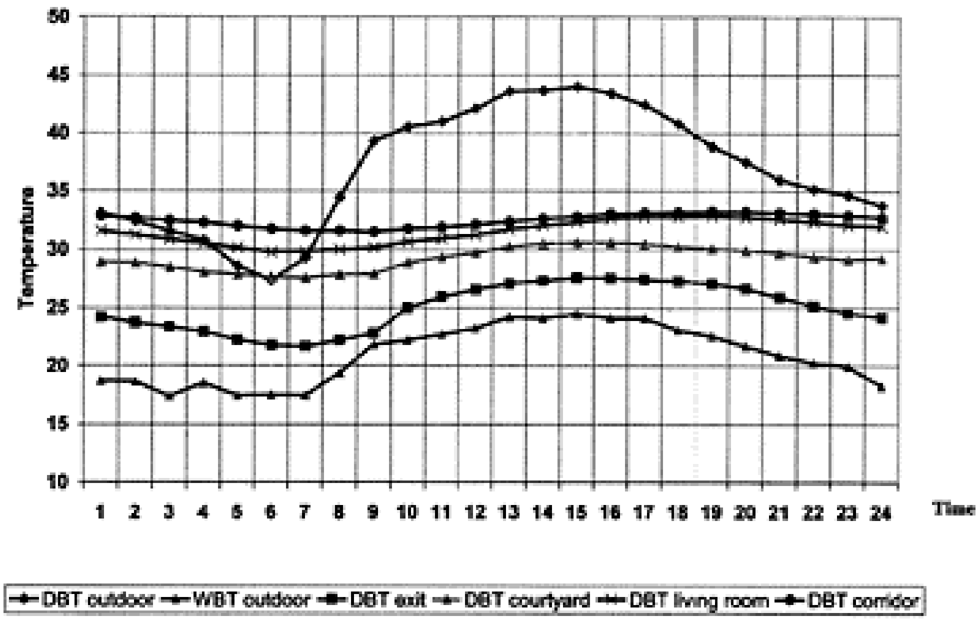


Figure 29. The thermal performance of the courtyard and cooling tower (Al-Hemiddi and Al-Saud 2006)

A similar experiment by Al-Saud and Al-Hemiddi (2001) was conducted on the same house (Fig. 30), to examine the cross ventilation effect, but with different variables, in three phases, as follows:

- Unshaded window, closed all times
- Shaded window, closed all times
- Shaded window, closed during day and ventilated at night by a fan at three speeds

Four parameters were produced for the assessment criteria: outdoor temperature, window-shading condition, thermal mass of the room, and ventilation rate.

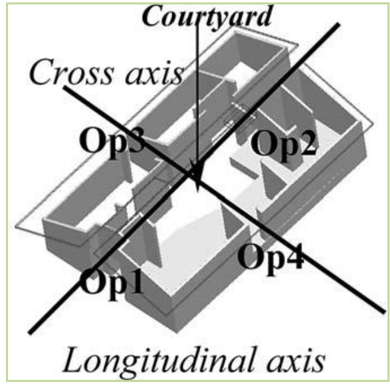


Figure 30. The study model (Al-Hemiddi and Al-Saud 2001)

The measurements readings proved that the internal temperature of the courtyard never exceeded the external temperature. Based on this fact, it was concluded that the courtyard along with the cross ventilation methods have a significant cooling effect on the interiors. Furthermore, the authors suggested applying these strategies on multi-storey buildings.

Rajapaksha, Nagai and Okumiya (2002) investigated the potential of the courtyard integration for passive cooling in single-storey high mass building in warm humid climate (Sri Lanka). An internal courtyard was utilized in order to optimize the natural ventilation and minimize indoor overheating conditions. Additionally, the indoor airflow patterns were controlled through the composition between the envelope openings and the courtyard. Computer Fluid Dynamics Analysis (CFD) was used to identify several airflow patterns.

The study stated that the effectiveness of the high thermal mass and shaded windows is dependent on the optimum exposure of the building to the air movement, which can enhance a greater surface-air contact. The goal was to provide some guidelines to manipulate the courtyard-building composition to lower the indoor temperature in warm humid climates.

The study house was utilized for five different configurations through opening and closing the major airflow access points in the house envelope. The monitoring was conducted on site from 12 April to 3 May. The paper discussed the results of the minimum and maximum air temperature and their corresponding airflow rates. Later the airflow patterns and airflow rates were simulated using the CFD. However, the paper attempted to extend the comfort zone to higher humidity and temperature by utilizing higher air velocities, Fig. 31.

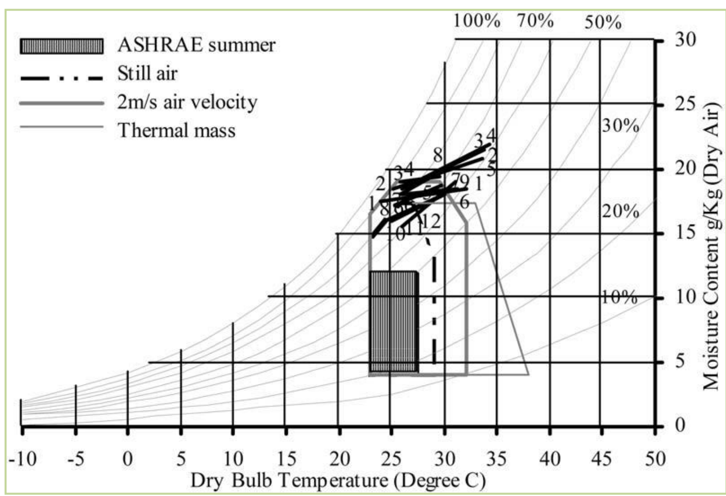


Figure 31. The extended Building comfort zone with the thermal mass and air velocities utilization (the legend "Still air" should be read " 1 m/s air velocity" as per the text of Rajapaksha et al 2002) (Rajapaksha 2002)

The paper built on the findings of other different studies, which state that an air velocity of 1 m/s is capable of extending the upper limit of comfort Dry Bulb Temperature (DBT) by 3.7 °C under warm humid conditions, with a clothing level of less than 0.5 clo (light clothing) and activity level less than 1 met. Given that the neutrality temperatures there were within 27.3-28.5 °C, the natural ventilation could extend the comfort zone up to 32.0 °C, Fig. 32.

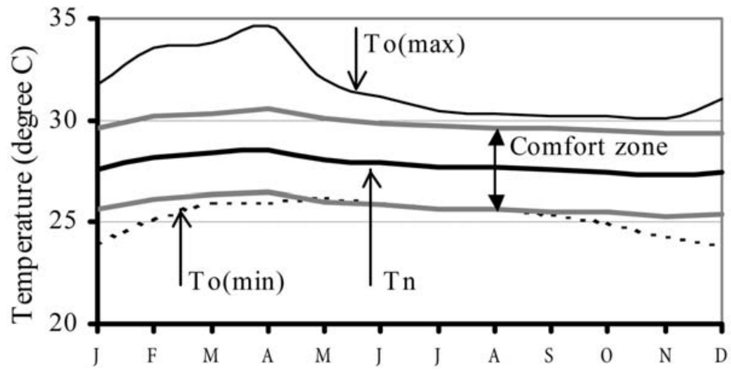


Figure 32. Pattern of neutrality temperature and comfort zone with relation to DBT (Rajapaksha et al 2002)

However, the dry bulb temperature remained above the extended upper limit during February to May. Thus, a strategy to reduce the maximum indoor air temperature was required in addition to the provision of indoor airflow.

The investigated building utilized a number of passive strategies, such as:

- A rectangular courtyard was located in the center, covering one tenth of the building footprint
- The plan depth around the courtyard was minimized for better potential of cross ventilation
- High mass building fabric (brick walls)
- Four major openings to enhance cross ventilation
- One third of the courtyard was covered with water to enhance evaporative cooling

- Openings were located at lower levels to enhance the potential for airflow due to stack effect during the night

In addition, the measurement points were located in the courtyard and selected indoor spaces. The measured data were the air temperature, the relative humidity at three different heights and the wind velocities.

The courtyard was monitored for 10 days with five different configurations with regard to the composition of the major openings, only two of them were represented in this paper, which were the worst and the best indoor climate modification:

- Case 1: during the daytime, openings on the external envelope were kept closed; building was ventilated only from the courtyard top
- Case 2: openings at the ends of longitudinal axis were kept open during daytime, in addition to the courtyard top

Measurements showed a reduction in the courtyard air temperature below the ambient level in both cases, yet a clear variation in the values was observed. Case 1 showed a reduction of only 0.7 °C, whereas in case 2 the reduction reached 2 °C below the ambient maximum during the daytime, Figs. 33 and 34.

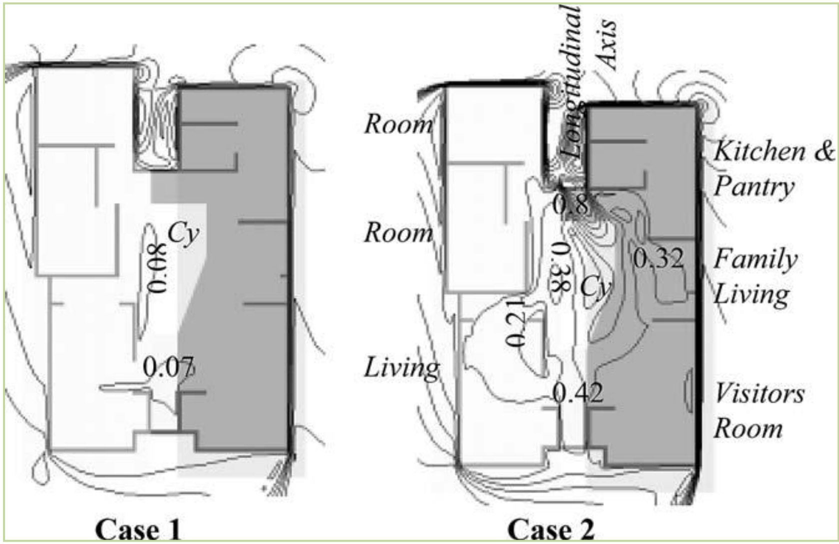


Figure 33. Simulated airflow patterns in case 1 and 2 (Rajapaksha et al 2002)

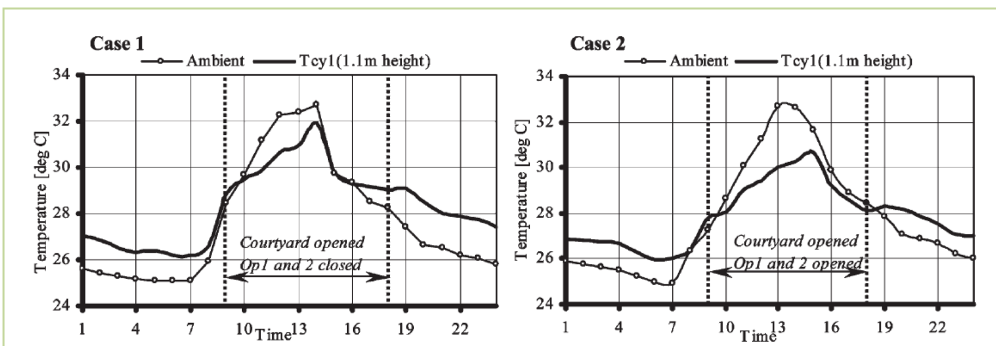


Figure 34. Temperature in case 2 was lower by 2 °C, whereas in case 1 was lower by 0.7 °C only (Rajapaksha et al 2002)

The air movement was observed close to the openings in case 2, the measurements indicated the availability of ventilation between 0.2 – 0.4 m/s during night time, whereas air movement was not observed in case 1. Furthermore, a variation of air velocities was observed close to the openings in case 2, which enhanced the ventilation due to the stack effect of temperature differences. Such an effect was not visible when the house was ventilated through the courtyard only, Fig. 35.

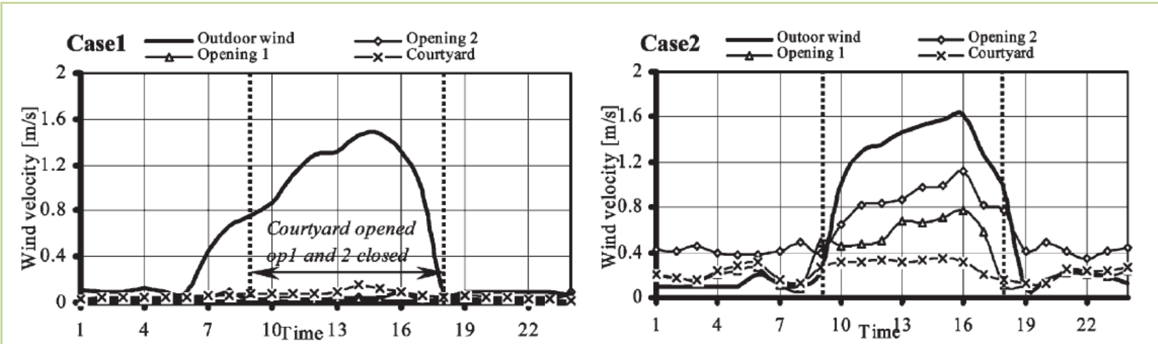


Figure 35. Air velocities at openings compared with ambient and courtyard in case 1 and 2 (Rajapaksha et al 2002)

According to the authors, Ventilation occurs when openings are available at points exposed to different levels of air pressure due to the temperature difference between indoors and outdoors. The same cases were simulated using CFD analysis; the results of the airflow rates were calculated then compared to the results of the field investigation. Figure 36 shows the correlation between the values of both methods, which proofed a reasonable accuracy of the CFD.

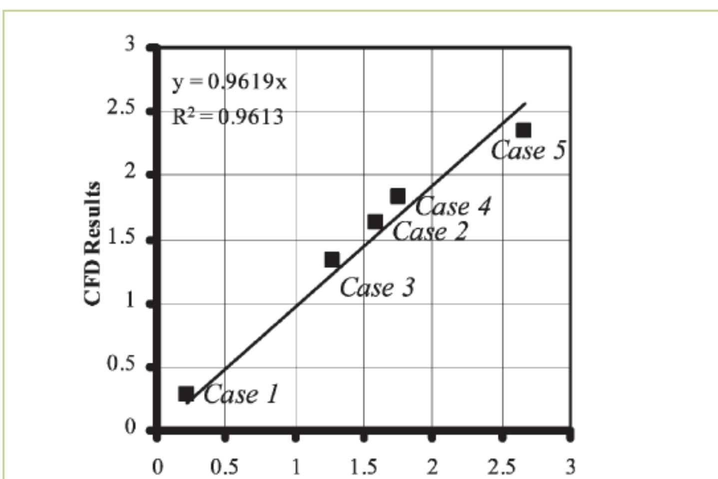


Figure 36. Comparison between CFD results and field investigation (Rajapaksha et al 2002)

The CFD analysis showed that the courtyard in case 2 acted as a suction zone inducing airflow thus optimizing the high thermal mass walls to the incoming air. The air traveled from openings 1 and 2 through the indoor spaces and finally discharged into the sky through the courtyard. Furthermore, the courtyard did not admit any airflow from the sky opening but acted as an "upwind air funnel" to discharge the indoor airflow into the sky.

In case 1, the courtyard acted as suction zone and admitted the airflow from the sky above. The air entering the courtyard tried to find the way out into the sky through the same opening, which created a vortex on the top. Part of this air traveled into the interiors but stagnated as the openings were closed, Fig. 37.

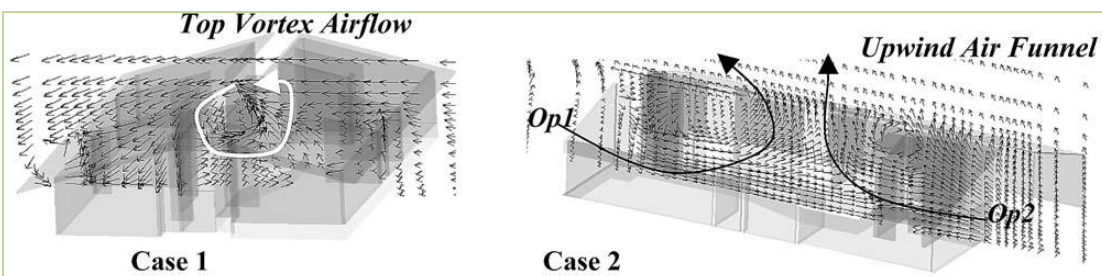


Figure 37. Vertical distribution of the simulated airflow patterns, case 1 with 'A top vortex'; case 2 with an 'Up wind air funnel' (Rajapaksha et al 2002)

Consequently, the field observation and computer simulations explored the potential of utilizing the courtyard for passive cooling in a single storey high-mass residential building in a warm humid climate. However, better indoor thermal modifications were observed when the courtyard acted as a funnel discharging indoor air into the sky, rather than the courtyard acted as a suction zone inducing air from the sky, as suggested from conventional knowledge. Additionally, it was found that the optimum flow rate that corresponds with the best thermal modification (more than 1 °C below the ambient level) is between 1.5 – 2.0 ACH.

Sharples and Bensalem (2001) conducted a comparison between the airflow in the courtyard and atrium building models located within an urban setting. Six different courtyard and atrium pressure regimes, positive pressure and suction, were examined using a wind tunnel experiment, as shown in Fig. 38. The cases were:

- Open courtyard, no roof, positive pressure
- Atrium pitched roof, no openings
- Atrium pitched roof, small area of openings in leeward side
- Atrium pitched roof, large area of openings in leeward side
- Atrium pitched roof, small area of openings in windward side
- Atrium pitched roof, openings in leeward and windward sides

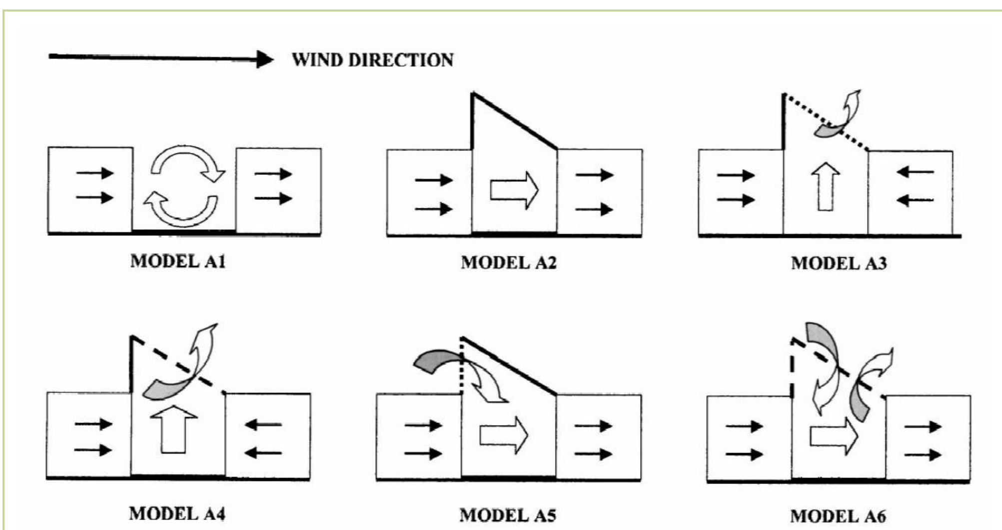


Figure 38. Courtyard and atrium roof ventilation strategies used in the study (Sharples and Bensalem 2001)

Airflow rates were measured using a wind tunnel and it was concluded that an open courtyard in an urban setting was found to have weak ventilation performance, especially when the courtyard was perpendicular to the oncoming wind.

The best ventilation performance was on the roofs positioned to face negative suction pressures when winds were perpendicular to the building. For the roofs on the positive pressures side, a large surface area and a great number of openings were needed to be utilized to enhance the ventilation effect.

2.7. Environmental Design Guidelines

The most effective way to reduce energy consumption in the house is to lessen the dependence on the active systems. This can be achieved through climatic-adapted passive design. In this section, some of the fundamental design strategies will be explained based on the previous literature.

2.7.1. Orientation

The house orientation, according to Koch-Nielsen (2002, p. 45), should be based on the building interaction with the sun as well as the prevailing wind. The greatest intensity of solar radiation is received by the horizontal surfaces, whereas the east and west facing surfaces receive the most solar radiation among the vertical surfaces. The east-facing vertical surfaces receive the radiation in the early morning while the west-facing surfaces receive it in the late afternoon.

It is stated by Koch-Nielsen that north- and south-facing vertical surfaces receive the minimum radiation in latitudes close to the equator, which is the case in the city of Dubai. However, the heat gain absorbed by the west and east walls can be reduced by increasing the insulative properties, thermal mass and shading devices. Another strategy is to allocate the spaces behind them for midday or night activities. Brown calls this strategy "migration", which means, "moving from one space to another to maintain thermal comfort" (1985, p. 115).

Additionally, in the courtyard house type, the courtyard can be manipulated to achieve the proper orientation in plots that are shaped by the streets alignments or cannot be oriented properly.

As for the wind, the house can be oriented according to the prevailing wind in order to maximize the benefits of the natural ventilation. On the other hand, by orienting the house to 45° to the wind direction, greater pressure will hit the house thus a better internal air distribution can be achieved due to the increased suction effect (Koch-Nielsen 2002, p. 45).

2.7.2. Spacing and Configuration

In the hot dry regions, the compactness of houses is very essential to provide the maximum shading and minimum solar exposure. Consequently, the courtyard house as an introverted form utilizes the shading and ventilation in the compact urban fabric.

The courtyard house may be designed to achieve the adequate daylight penetration yet avoid the solar excess heat gain. Furthermore, it needs to promote the cooling breeze while avoiding the dusty wind.

2.7.3. Openings Design

The opening size, location and treatment greatly affect the heat gain, air ventilation and light penetration into the house.

The openings designed for daylighting should consider avoiding the direct sunlight and glare by opening only to the courtyard or using screening elements such as "Mashrabia". Mashrabia is a traditional element made of wood, which conducts heat slowly, and acts like a light diffuser in addition to its role in providing shade and ventilation without compromising the privacy as shown in Fig. 39.

Figure 39. Mashrabia as a screening element of windows (Personal Archive)

As for the ventilation, small openings on the windward sides and large ones on the leeward side create higher velocities thus enhancing the cross ventilation. Furthermore, the height variation on two opposite walls creates a good internal air distribution, as shown in Fig. 40 below.

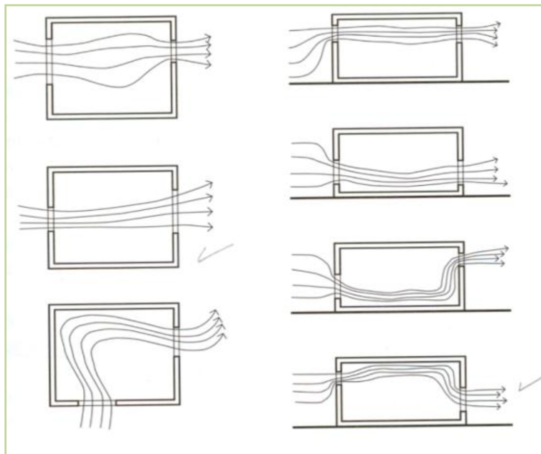


Figure 40. Vertical sections and plans show the effect of variation in height and size on the air distribution and speed (Koch-Nielsen 2002)

On the other hand, the stack effect can be achieved by locating the openings at different heights, which increases the air movement due to the temperature-generated pressure differences across openings. Both types of openings are recommended to be operable, closed during the day and open during the night (Koch-Nielsen 2002, pp. 88 & 89).

2.7.4. Shading Devices Design

The shading devices are wall protection methods, which can reduce the solar radiation and glare, and thus minimize the heat gain into the house. As previously mentioned, with regard to the house orientation, the east-and west-facing walls are exposed to the highest solar radiation during the day. Therefore, proper vertical shading devices should be applied because the sun passes on low angles in the early morning and late afternoon, where the north- and south-facing walls are exposed to a little solar radiation. Therefore and due to the high sun angels, horizontal shading devices should be integrated (Koch-Nielsen 2002, pp. 92- 94). On the other hand, shading devices should be made of light and high-reflectivity materials to avoid heat absorption.

2.7.5. Insulation Materials

The insulation materials play a great role in the house design for climate control, thus reducing the energy loads substantially. They control the heat transfer between the outside surface and the inside surface, based on their thermal conductivity properties. Koch-Nielsen (2002, pp. 102 & 103) defines two values with regard to the materials insulative properties:

- λ Value is the rate of heat flow through a volume of material with temperature difference between the two sides, and measured in W/m °C
- U Value is calculated based on the material's thickness, the value of 1/λ and the resistance on the outer and inner surfaces, measured in W/m^2 °C

Materials with high U value have low insulative properties, whereas materials with low U value have high insulative properties.

Humidity affects the absorbtivity of the heat due to the increased conductivity in the material. Some insulation materials do not absorb humidity such as rock or glass wool; others can store humidity to certain level without losing the insulative capacity such as natural wool and adobe structure (Koch-Nielsen 2002, p. 105).

2.8. Summary of Literature Review Findings

The previous studies conducted on the courtyard house typology have been presented in the literature review. In summary, the history, social and cultural aspects have been discussed briefly, in addition to the form and different geometries parameters. Studies carried out on the environmental performance, with respect to the thermal, shading, daylight and ventilation, have been represented comprehensively. Some other guidelines and design generators, based on the relative books, have been described to draw a baseline model for this study proposal.

The findings are summarized as follow:

Climate: Most of the studies were relative to the hot arid climate as little literature discussed the warm humid and other climates. The high humidity is a climatic issue in Dubai that can be resolved with similar strategies applied in the warm humid climate, which is basically based on the cross ventilation utilization.

Height: The represented studies were concerned with the single-family or one- to two-storey houses. Two papers discussed the effect of the increased height on the environmental efficiency of the house. It was found that the efficiency of the courtyard drops when the house height exceeds 10 floors where it is more efficient to turn the courtyard into an atrium in that case (Aldawoud 2007, and Aldawoud and Clark 2007).

Another study by Hakmi (cited in Edwards et al 2006, pp. 178- 201) represented a different proposal for courtyard multi-storey housing in different configurations. Hakmi argues the environmental efficiency of such configurations, yet no assessment methodologies were conducted to validate this argument.

Daylight and shading: The most recommended shape for in the hot arid climate is the deep and narrow courtyard with a low aspect ratio, which means less exposure to the solar radiation (Muhaisen 2005, and Muhaisen and Gadi 2005).

Airflow and Ventilation: Some papers emphasize the importance of adequate ventilation on the thermal condition of the courtyard house (Meir et al 1995). This includes the effect of the stack ventilation where the courtyard acts like a thermal sink (Al-Saud and Al-Hemiddi 2006), in addition to the cross ventilation role in enhancing the coolness of the interiors (Al-Saud and Al-Hemiddi 2001 and Rajapaksha et al 2002).

However, the previous studies fell short of assessing these environmental aspects on the courtyard housing typology in midrise buildings. There are insufficient studies to test the climatic efficiency of such proposals. Those findings of the literature review will be incorporated in the suggested model, and appropriate selected design guidelines will be applied in the hot-arid climate context.

Chapter 3: The Research Proposal

3.1. Study Motivation

"Climate and the need for the shelter" is a historical analogy. The climate variation led to a variation in the architectural response, which influenced the housing typologies. Igloos in the Eskimo or the Japanese house forms are examples of the building response to the climate (Rapoport 1969). According to Rapoport (1969), our region has developed both the courtyard and other forms, though the first is more related to the cultural and climatic issues. The courtyard houses in this urban fabric were always good examples for the bioclimatic typologies where their residents can enjoy the outdoors breeze with a minimum energy use while not separated from their climate and culture. This typology is one of the oldest in many regions of the world, such as the Middle East, Latin America, China, and Europe. On the other hand, the use of inappropriate building forms imported from other regions falls short of providing a shield from the discomfort caused by harsh climates. In the last years, the architecture lost its connection to the place due to the presence of the active systems of cooling and heating (Koch-Nielsen 2002, pp. 15 & 16). Furthermore, the passive systems lost the acceptance as they were seen as being part of an old tradition and non-modernistic practice.

On a larger scale, Fig. 41 shows that the courtyard concept was found in the old cities in the Middle East in an urban setting, where houses are embracing a large, public and central courtyard. Each house has rooms that embrace again a private courtyard. On the social and cultural levels, the city courtyard, in the form of a public plaza, was a positive void where all public interactions and gatherings could take place.

"By simple analysis it becomes quite understandable how such a pattern came to be universally adopted in the Arab world. It is only natural for anybody experiencing the severe climate of the desert to seek shade by narrowing and properly orienting the street, to avoid the hot desert wind by making the streets winding, with closed vistas".

(Fathy 1973)

Figure 41. Public and private courtyard on different scales: house and city (Edwards 2006)

It is stated that the courtyard houses are good representation of the Arabian Gulf region in terms of its appropriateness with regard to the climate, culture and social conditions.

In the United Arab Emirates, The rapid economic growth has greatly affected the built environment. Therefore, the housing typologies have been imported from the western countries rather than employing the traditional concepts into contemporary frames. Thus making the freestanding house located in the center of the plot a typical housing form in the UAE (Mitchell 2006, p. 173), Fig. 42.

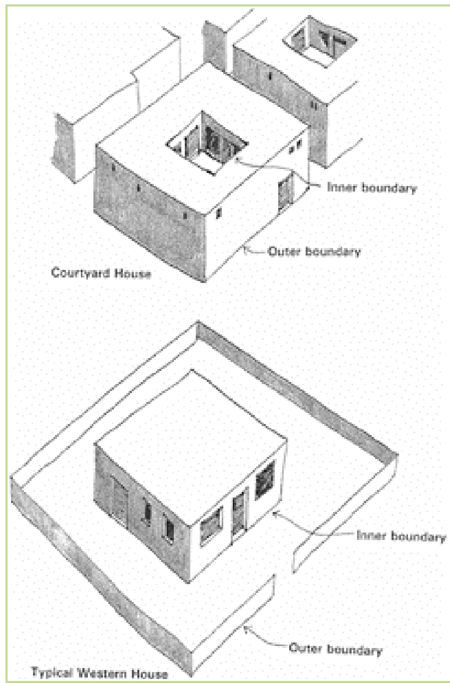


Figure 42. The courtyard vs. the freestanding forms (Edwards 2006)

How efficient is the integration of the courtyard into the midrise housing in terms of response to hot-arid climate, compared to other applied forms of architecture?

How efficient is applying the courtyard concept on the midrise apartment buildings compared to that in the low rise single houses?

This research will try to answer these questions within the hot-arid climate context by assessing the environmental variables such as sun, temperature and wind on two urban forms: a proposed block of midrise courtyard housing (introverted) and the typical form where the apartments are overlooking the outside (extroverted).

An extensive reading of the previous studies of courtyards within the traditional context has been carried out to analyze the environmental performance with respect to the climate and culture. This study will be based on these findings and recommendations, such as the design generators or guidelines, presented in an earlier section, to achieve a model with an optimum performance.

This model is tested against the chosen climate using computer simulation software, along with the modern form model. Results are processed then compared. A new affordable housing typology is proposed based on maximizing the benefits of the courtyard as a climate moderator and responding to the need for contemporary small units. However, this research argues that the courtyard in midrise buildings is possible, where a more sustainable and responsive form occupying the plot yet achieving a higher density than the single-family form. This form avoids the spread-out cities and results in less dependence on automobile movements.

3.2. Aims and Objectives

This research examines the possibility of the integration of the courtyard into midrise housing buildings in hot arid climates. A proposal, designed with reference to the literature review findings, will be suggested and compared to the conventional housing model. The proposal is largely a continuation of Hakmi's approach (2006) for the midrise and multi-storey courtyard housing.

The aims of this research are to:

- Assess the suitability and appropriateness of the proposed model in the hot arid climate
- Identify the advantages of the proposed model.

The objectives are:

- Assess the environmental performance of the proposed model using computer simulation (IES Virtual Environment) with respect to:
  - Thermal analysis
  - shading and daylight analysis
  - ventilation and airflow patterns.

- Estimate the energy consumptions (cooling loads) based on a set of fixed and variable parameters:
  - Orientation: fixed
  - Height/number of storey: variable
  - Glazing type: variable
  - Wall thickness: variable
  - Insulation material: variable
  - Insulation material thickness: variable.

In order to achieve that, the following procedures have been carried out in the previous chapter:

- Review the courtyard's historical, social and cultural dimensions.
- Review the conventional courtyard house models with respect to their climatic performance and efficiency.

- Obtain climatic design guidelines to draw a base/reference model for a midrise courtyard house.

3.3. Proposal Description

This study examines the courtyard midrise housing form in the context of the hot arid climate, with respect to variable parameters. These parameters include number of storey (height), glazing type, wall thickness, insulation material and insulation thickness as shown in Table 5. These parameters provide key measures to the thermal comfort, daylight, shading and ventilation, as well as the overall energy consumption.

Firstly, selected variables will be fixed then assessed in both forms: the conventional and the courtyard midrise housings. The two forms share an equal built-up area. The results criteria will be produced, then both forms will be compared, in order to investigate the appropriateness of the courtyard integration in the midrise housing.

Secondly, the courtyard midrise form will be tested against different variables of the proposed study parameters, to achieve an optimum energy performance model that best represents the given climate, as per Tables 6 and 7.

Lastly, a six-level courtyard model with these optimal variables will be simulated and then compared to the conventional model to represent the optimum performance in terms of the energy reduction.

Table 5. The variables in relation to the assessment criteria

Parameter/ Assessment Criteria	Number of Storey	Glazing Type	Wall Thickness	Insulation Material	Insulation Thickness
Thermal	x	x	x	x	x
Shading	x				
Daylight	x				
Airflow	x				
ENERGY REDUCTION	x	x	x	x	x

Table 6. Matrixes of variables of the courtyard model- highlighted cells are the reference model

PARAMETER (VARIABLE)	Number of Storey	Glazing Type	Wall Thickness	Insulation Material	Insulation Thickness
COURTYARD MODEL	4	Single Glazed	15 cm	Glass-Fiber Quilt	2.5 cm
	6	**Double Glazed (Low-e)**	20 cm	**EPS (Styrofoam)**	**5.0 cm**
	8	Triple Glazed (Low-e)	**25 cm**	Phenolic Foam	7.5 cm
	10		30 cm	Cavity [ASHRAE]	10 cm
			40 cm	Cellular Polyurethane	

Table 7. Studied parameters of the conventional model

PARAMETER (FIXED)	Number of Storey	Glazing Type	Wall Thickness	Insulation Material	Insulation Thickness
CONVENTIONAL MODEL	6	Double Glazed (Low-e)	25 cm	EPS (Styrofoam)	5.0 cm

The study scenario steps from generic to specific as in Fig. 43. First, a comparison of the total energy consumption between conventional and courtyard forms (extroverted and introverted) is conducted, while all other parameters are constant (Fig. 44). Next, different variable within the courtyard form will be examined and compared in terms of the energy consumption per square meter, knowing that the total area will vary from one variable to another (Fig. 45). Again, the courtyard model with these optimum parameters will be tested against the conventional model.

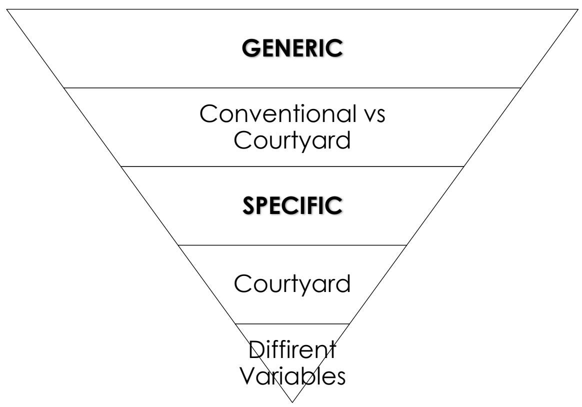


Figure 43. The study methodology

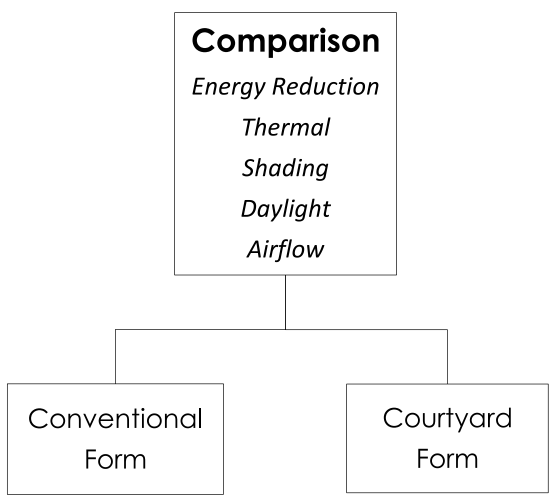


Figure 44. First step: comparison between conventional and courtyard forms

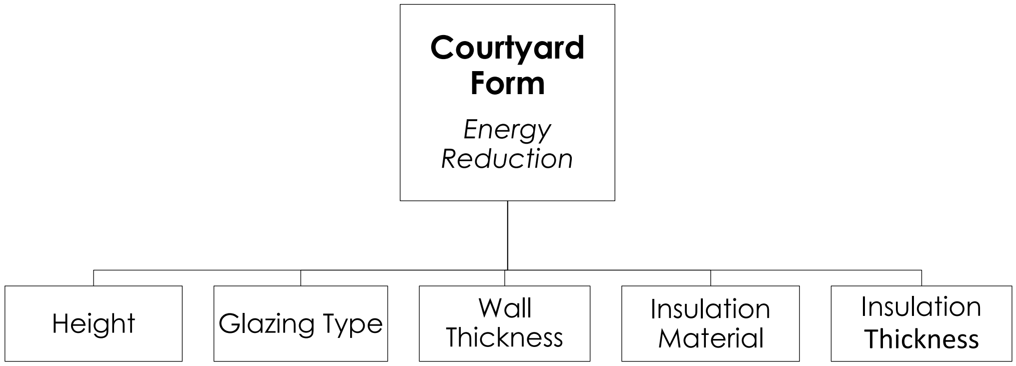


Figure 45. Second step: assessment of different variables within the courtyard form

3.3.1. Step 1: Assessment of Conventional versus Courtyard Form (Generic)

The annual energy consumption, along with other data, will be compared in both forms: without and with the courtyard incorporation, as shown in Fig. 46. The two forms constitute six levels of typical floors and both are formed from units of an equal area (Fig. 47) in order to maintain the same overall built up area.

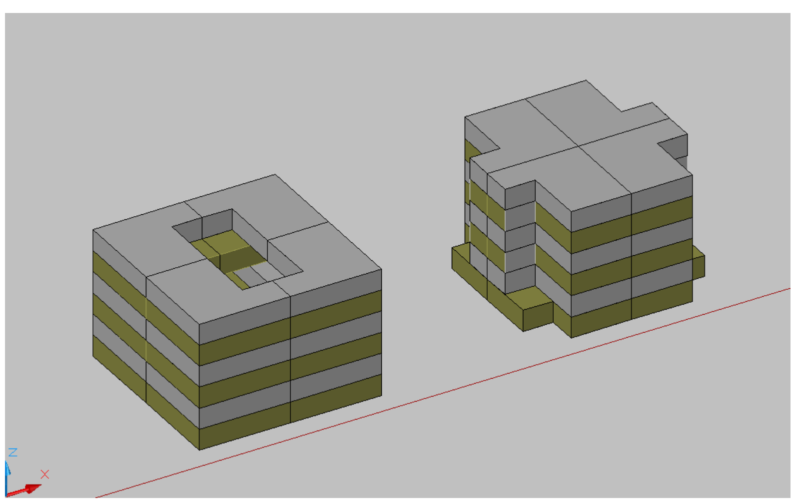


Figure 46. Comparison between six levels of conventional (right) & courtyard forms (left) (AutoCAD 2007)

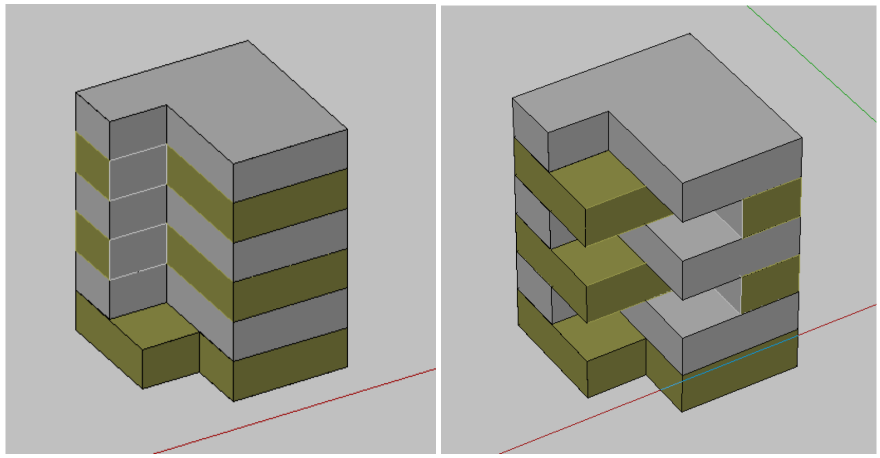


Figure 47. Two unit of same area for the two forms (AutoCAD 2007)

The midrise building is defined as a "moderately high building**:** a building of moderate height, about five to ten stories" (Encarta 2010). However, the selection of six-level height is based on the common practice in Dubai for the midrise housing buildings, which range from four to six levels, Figs. 48- 51.

Figure 48. The Greens- Dubai- seven levels
(Personal Archive)

Figure 49. The Gardens, Dubai, five levels (Personal Archive)

Figure 50. The international City, Dubai, five levels (Personal Archive)

Figure 51. The Downtown, Dubai, four levels around a courtyard
(Personal Archive)

In the courtyard model, this unit is repetitive every other floor which leads to unified indoor space (apartment). It also has a unified outdoor space (courtyard), except in the first level where the indoor space has a larger area than the ones in the upper levels. The unit is built based on 5 x 5 meter grid. All floors have the same courtyard to built-up area ratio, which is equal to 50/175, except the first level where this ratio is equal to 25/200. Furthermore, levels 2, 4 and 6 have the same identical configuration, whereas levels 3 and 5 have different configurations, Fig. 52.

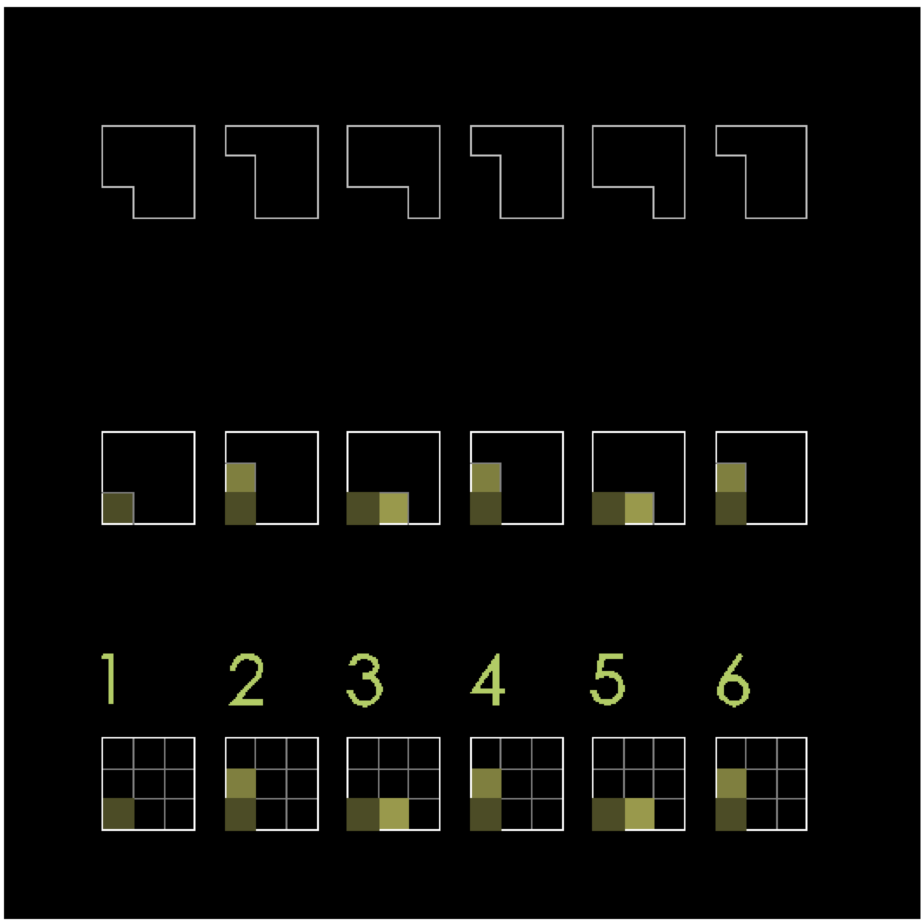


Figure 52. The unit forms six levels with the repetitive configuration every other floor (green shaded stands for courtyard) (AutoCAD 2007)

Moreover, four units (same type) are utilized to form an inner void in which the apartments' courtyards are all located around the inner void center to create an introverted courtyard-housing block. As for the conventional from, the same steps are followed, except that the four units are rotated around their solid ends and the apartments' courtyards are all located around the outer boundary to create an extroverted conventional housing block, Fig. 53.

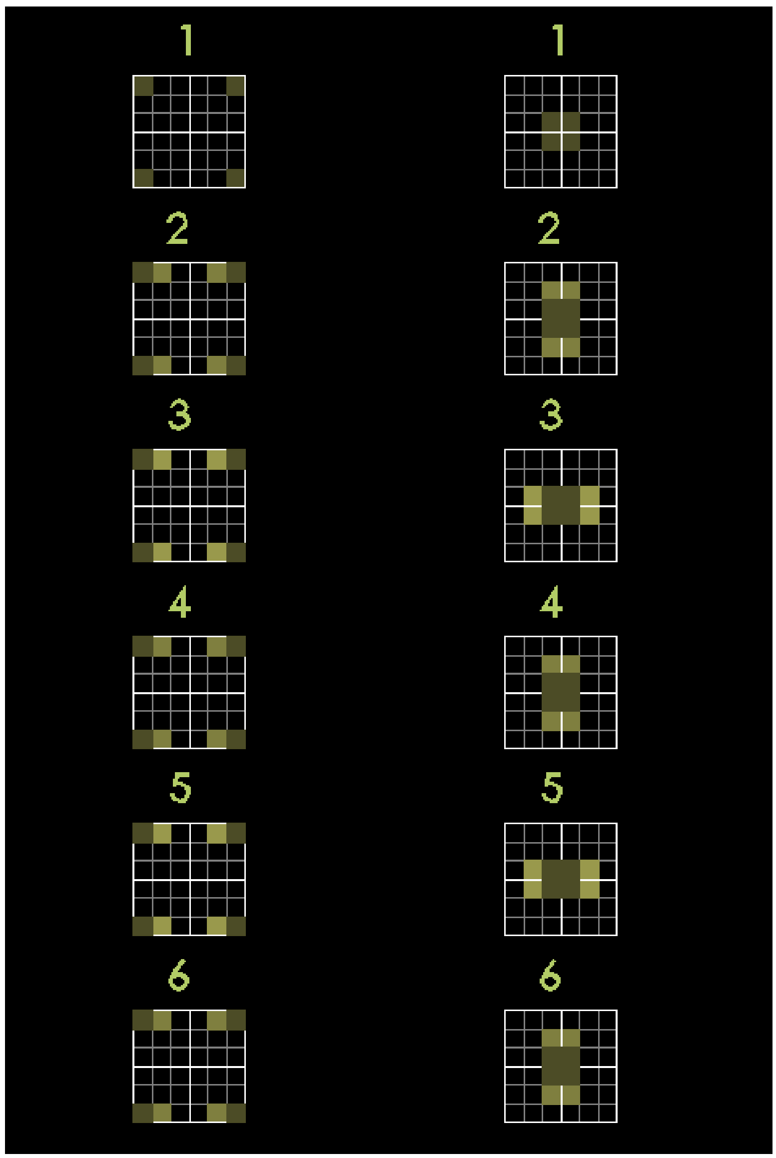
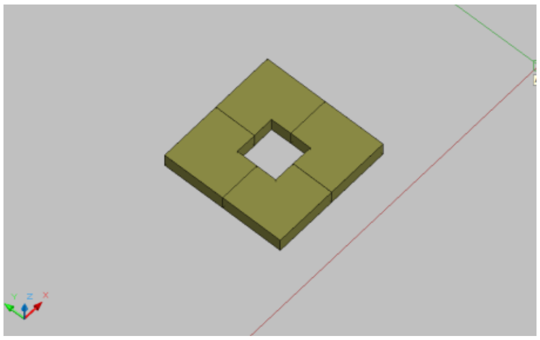
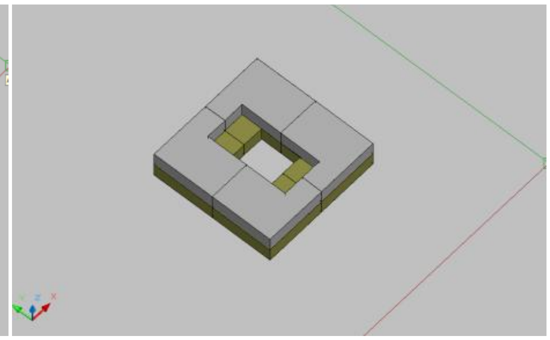


Figure 53. Conventional (left) and courtyard forms (right), green stands for courtyard/terrace (AutoCAD 2007)

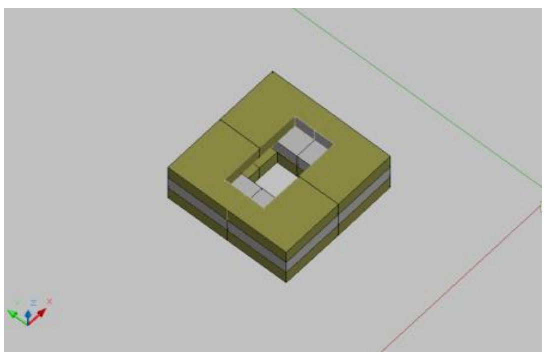
Figure 54 shows details of areas per each floor in the courtyard model.

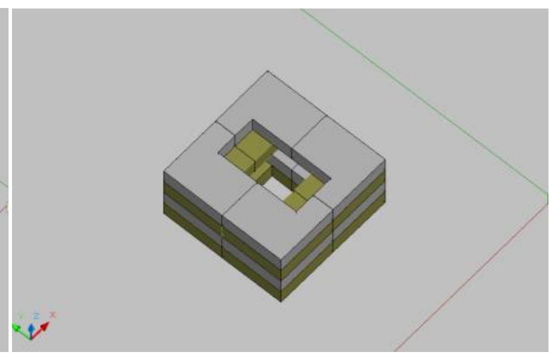




Level 1: CY/flat= 25/200 m²

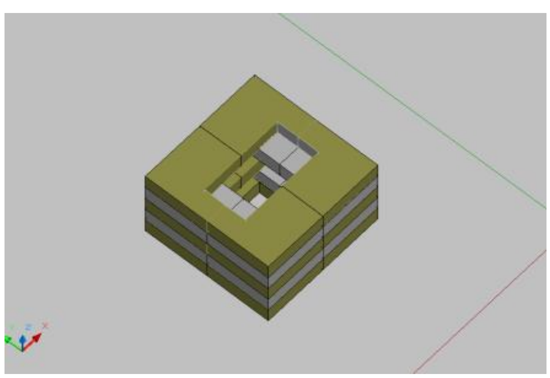
Level 2: CY/ flat= 50/175 m²

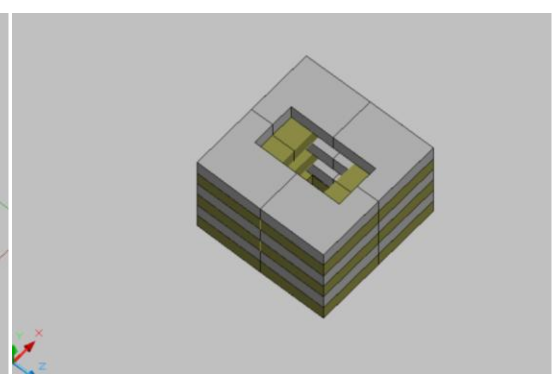




Level 3: CY/ flat= 50/175 m²

Level 4: CY/ flat= 50/175 m²





Level 5: CY/ flat= 50/175 m²

Level 6: CY/ flat= 50/175 m²

Figure 54. The courtyard form areas details for each level (AutoCAD 2007)

3.3.2. Step 2: Assessment of Different Variables within the Courtyard Form (Specific)

Variable 1: Height/Number of Storeys

The height from floor to floor is set to 3.5 m. The model is assessed in different heights within the midrise context: four, six, eight and ten levels. Consequently, the optimal height is decided based on the maximum reduction of the annual energy consumption. On the other hand, while assessing this variable the other variables remain constant as per the highlighted cells in Table 6.

Variable 2: Glazing Type

The courtyard model is assessed in different glazing types: single glazing, double glazing (Low-e) and triple glazing (Low-e). Table 8 summarizes the properties of these types.

Table 8. Glazing types Properties (IES Project Construction Library)

Glazing Type	U-Value (EN-ISO) W/m².K
Single Glazed	5.6928
Double Glazed (Low-e)	1.9762
Triple Glazed (Low-e)	1.4605

Variable 3: Wall Thickness

The courtyard model is assessed in different wall thicknesses: 15, 20, 25, 30 and 40 cm, to evaluate the impact of these variables on the overall energy consumption. Meanwhile, the other variables are set to constant as per the highlighted cells in Table 6.

Variable 4: Insulation Material

The insulation materials incorporated in the external walls improve the thermal comfort by reducing the heat loss in addition to the other benefits like moisture and fire resistance. Five insulation materials, listed in Table 9, are selected for the aim of this study as per the following:

- Dense EPS Insulation like Styrofoam (Expanded Polystyrene)
- Glass-Fiber Quilt
- Phenolic Foam
- Cavity Insulation [ASHRAE]
- Cellular Polyurethane

Table 9. Insulation Materials Properties (IES Project Construction Library)

Insulation Material	Conductivity W/(m.K)	Density kg/m³	Heat Capacity J/(kg.K)
Dense EPS Insulation like Styrofoam	0.025	30.0	1400.0
Glass-Fiber Quilt	0.040	12.0	840.0
Phenolic Foam	0.040	30.0	1400.0
Cavity Insulation [ASHRAE]	0.076	32.0	837.0
Cellular Polyurethane	0.020	24.0	1600.0

Variable 5: Insulation Material Thickness

The reference insulation material (Dense EPS Insulation) in the courtyard model is tested in different thicknesses: 2.5, 5.0, 7.5 and 10 cm, to evaluate the impact of the insulation thickness on the overall energy consumption. Meanwhile, the other variables are set to constant as per the highlighted cells in Table 6.

3.3.3. Step 3: Assessment of Optimum Courtyard Form versus Conventional Form

The courtyard form, with variables set to optimal based on the previous step outcomes, will be compared to the conventional form. The height will be fixed to the six-level model as per the first step settings. The result will draw the best parameters that can be incorporated in the courtyard form to achieve the highest energy saving in the given climate.

Chapter 4: Methodology

4.1. Climate in Dubai, UAE

4.1.1. Location: The United Arab Emirates

"The UAE lies between 22°50′ and 26° north latitude and between 51° and 56°25′ east longitude. It shares a 530-kilometer border with Saudi Arabia on the west, south, and southeast, and a 450-kilometer border with Oman on the southeast and northeast" (Wikipedia 2009), Fig. 55.

Figure 55. The United Arab Emirates map (Wikipedia 2009)

Dubai is one of the seven emirates of the United Arab Emirates (UAE). It is located south of the Persian Gulf on the Arabian Peninsula and is roughly at sea level (16 m/52 ft above). The emirate of Dubai shares borders with Abu Dhabi in the south, Sharjah in the northeast, and the Sultanate of Oman in the southeast.

4.1.2. Climate: Hot Arid

The climate of the UAE generally is hot and dry. The hottest months are July and August, when average maximum temperatures reach above 48° C (118° F).

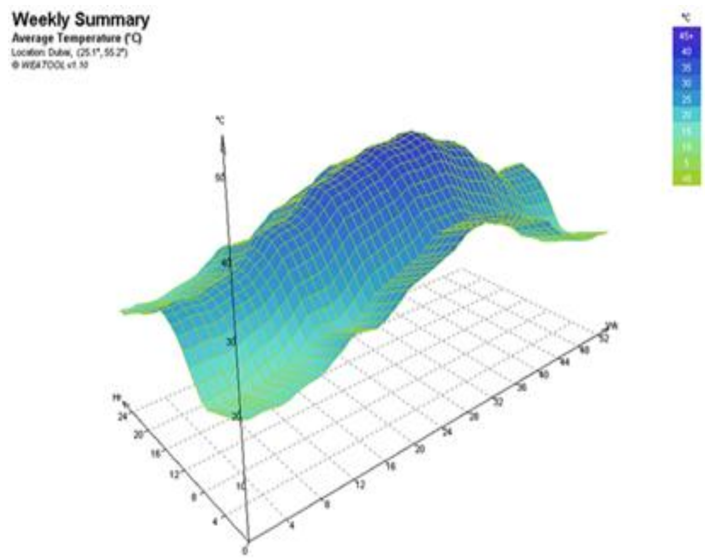


Figure 56. The weekly summary temperature (ECOTECT)

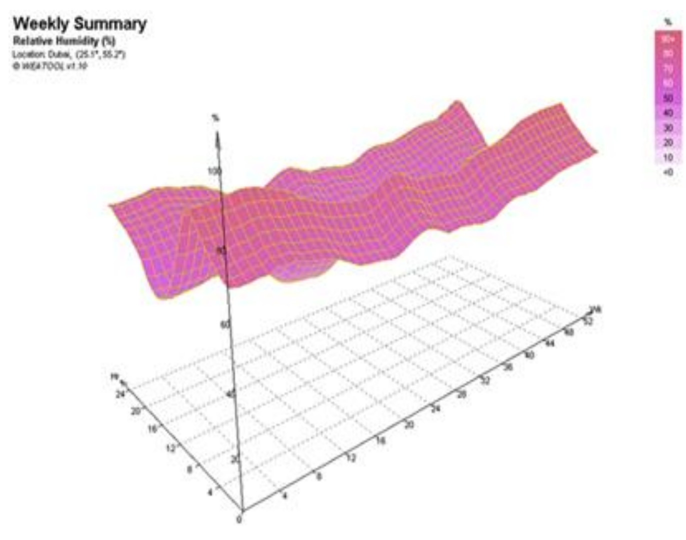


Figure 57. The weekly summary humidity (ECOTECT)

According to Köppen climate classifications (Wikipedia 2009), Dubai has a Dry (arid and semiarid) climate. Summers in Dubai are extremely hot, windy, dry, with an average high around 40° C, and overnight lows around 30 °C. Sunny days can be expected throughout the year. Winters are warm and short with an average high of 23 °C and overnight lows of 14 °C. Precipitation, however, has been increasing in the last few decades with accumulated rain reaching 150 mm per year. This does not affect the aridity of the area although it has increased the abundance of desert shrubs inland.

Table 10. Monthly weather data for Dubai (Wikipedia)

Weather data for Dubai [hide]												
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Average high °C (°F)	24.0 (75)	25.4 (78)	28.2 (83)	32.9 (91)	37.6 (100)	39.5 (103)	40.8 (105)	41.3 (106)	38.9 (102)	35.4 (96)	30.5 (87)	26.2 (79)
Average low °C (°F)	14.3 (58)	15.4 (60)	17.6 (64)	20.8 (69)	24.6 (76)	27.2 (81)	29.9 (86)	30.2 (86)	27.5 (82)	23.9 (75)	19.9 (68)	16.3 (61)
Precipitation mm (inches)	15.6 (0.61)	25.0 (0.98)	21.0 (0.83)	7.0 (0.28)	0.4 (0.02)	0.0 (0)	0.8 (0.03)	0.0 (0)	0.0 (0)	1.2 (0.05)	2.7 (0.11)	14.9 (0.59)
Source: Dubai Meteorological Office[38] 2008												

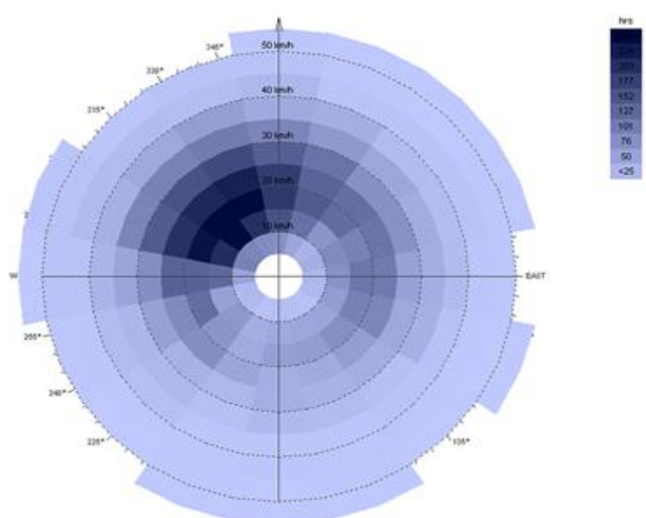


Figure 58. Wind rose in Dubai shows the prevailing wind from the north-west (ECOTECT)

Psychrometric charts describe the relationship between dry-bulb temperature, and relative humidity, on the horizontal and the vertical axes respectively. The Thermal Comfort Zone is defined according to temperature and relative humidity, as well as the occupants' involvements such as clothing and activity level. The UAE psychrometric charts reflect the natural lack of outdoors comfort zones, where the climate is plotted outside the comfort zone in summer, Fig. 59 and 60.

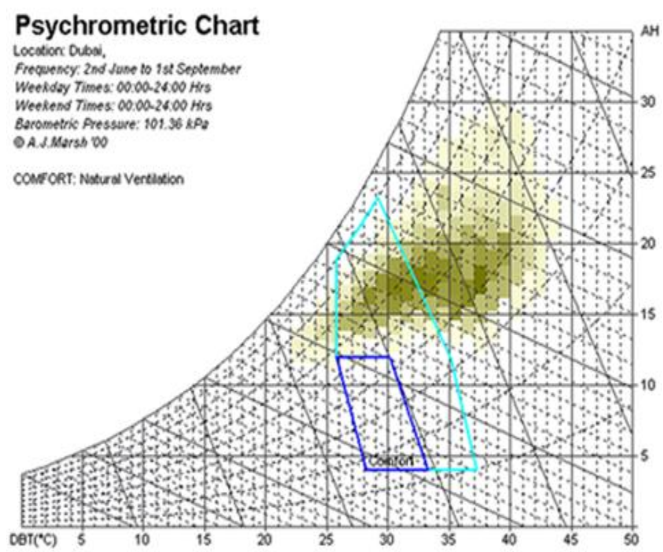


Figure 59. Psychrometric chart of Dubai in summer (Weather Manager)

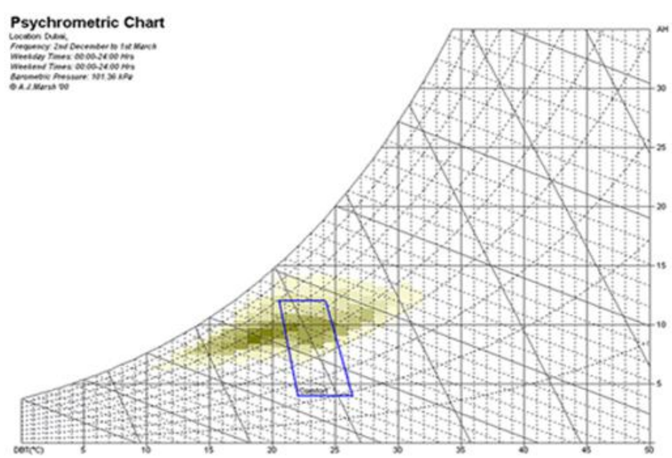


Figure 60. Psychrometric chart of Dubai in winter (Weather Manager)

4.2. Research Methodology: Computer Simulation

According to Muhaisen and Gadi (2006), thermal analysis can be undertaken using either calculations or computer simulations to simulate the interplay of the thermal performance into the building. There are variable software tools, which vary in the simulation methods and applications.

The computer simulation method is largely used within the architectural practice in all stages, especially in the concept stage, to assess the model response to the climate. Architects and designers can benefit from the computer analysis capabilities to evaluate multiple design alternatives earlier in the process. Thus, delivering more energy efficient buildings and sustainable architecture.

One of these simulation tools is Ecotect® by Autodesk®: "sustainable analysis tool that delivers a wide range of simulation and analysis functionality through desktop and web-service platforms. Powerful web-based whole-building energy, water, and carbon analysis capabilities converge with desktop tools to conduct detailed environmental simulations and visualize results" (Autodesk).

This research is conducted using another simulation tool, which is Virtual Environment (VE), by Integrated Environmental Solutions (IES). It is an integrated building performance analysis platform. IES provides a range of different analysis options and capabilities, which give detailed simulations of the building, such as building loads, carbon emissions, daylight, solar analysis and airflow. Furthermore, the software assesses the passive and renewable strategies, as well as compliance with the energy and environment regulations and codes.

The IES software is a package of various modules in which each deals with a certain calculation. An overview of these modules is presented in the followings:

4.2.1. ModelIT: Building Modeller

The model can be created and edited as a simple mass or more detailed geometry. Additionally, other files can be imported or attached from other software such as AutoCAD DXF files and SketchUp files.

4.2.2. SunCast: Solar Shading Analysis

This module analyzes the solar gains into the building and assesses the shading efficiency to reduce the heat gain and direct solar radiation during hot days. Furthermore, it generates images and animations from a model created by the IES ModelBuilder (ModelIT).

4.2.3. ApacheSim: Thermal Calculation and Simulation

This module is a dynamic thermal simulation tool based on mathematical modeling of the heat transfer processes within and around a building. Results from ApacheSim are viewed using the program Vista. Data from other modules like SunCast and CFD are integrated into the calculations of the simulation results.

Nevertheless, the module is capable of producing various results related to the building's heating and cooling loads, total energy and carbon emissions.

4.2.4. Vista: Results Analysis

This module is part of the thermal group applications. It reviews and analyzes the results of the simulations carried out using the thermal modeling tools. The data can be represented graphically or numerically on multiple variables at selected dates or months.

4.2.5. VistaPro BETA: Advanced Analysis

This is an advanced tool for the thermal calculations analysis; bulk airflow visualization and 3D color coded results, as well as wind rose.

4.2.6. FlucsDL: Day Lighting Analysis

This module allows calculating illuminance and daylight levels on any surface of the model. These calculations are integrated in the overall energy consumption results.

4.2.7. MicroFlo: CFD

Computational Fluid Dynamics (CFD) model is used to analyze air movement in details, assess air patterns and visualize temperature distributions in the model. It is related to the numerical simulation of fluid flow and heat transfer processes occurring within and around building given specified boundary conditions including the effects of climate, internal energy sources and HVAC systems.

4.3. Software Validation

Peer reviewed papers utilized the selected software as a simulation tool, which support its validity for other studies. Muhaisen and Gadi (2006) utilized IES (Virtual Environments) to carry out the investigation on a similar study: The effect of the courtyard proportions on the solar heat gain in buildings. According to them, the IES program is an integrated package of applications with a single integrated Data Model, in which the data input for one application can be used by the others. In their conducted study, only three of these applications were used to carry out the investigations; these are *ModelIT, SunCast* and *ApacheSim*. The IES software is chosen to perform the research analysis due to its accuracy and available capabilities such as the airflow patterns analysis (CFD) and the advanced thermal calculations. Moreover, the CFD analysis results were validated by comparing them to the field investigations in Rajapaksha's (2002) research paper presented earlier.

4.4. Simulation Process

In this section, the computer simulation process is explained in details until the results are given for analysis.

4.4.1. Design Weather Data

Firstly, the weather data related to Dubai, the research location, are extracted from the software selection wizard of APLoacte, which is set to Dubai/Int'l Airport, UAE. Figures 61- 65 show the climatic data given by ApacheSim's database.

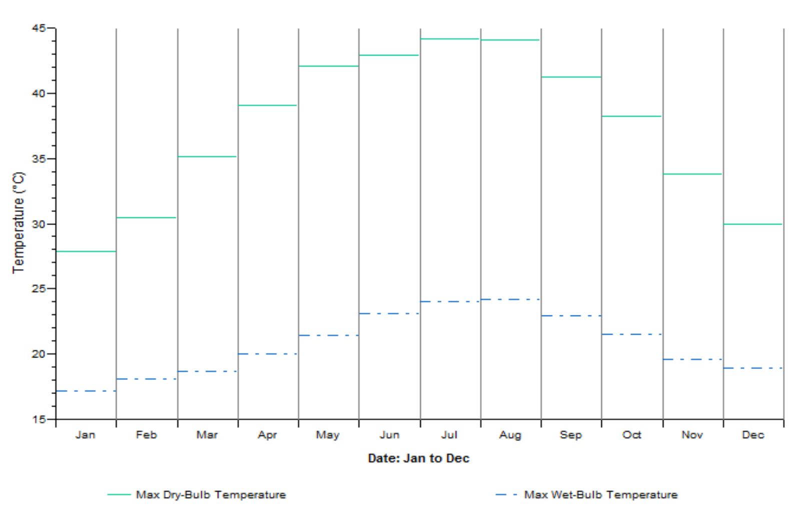


Figure 61. Annual temperature from January to December- Dubai (IES)

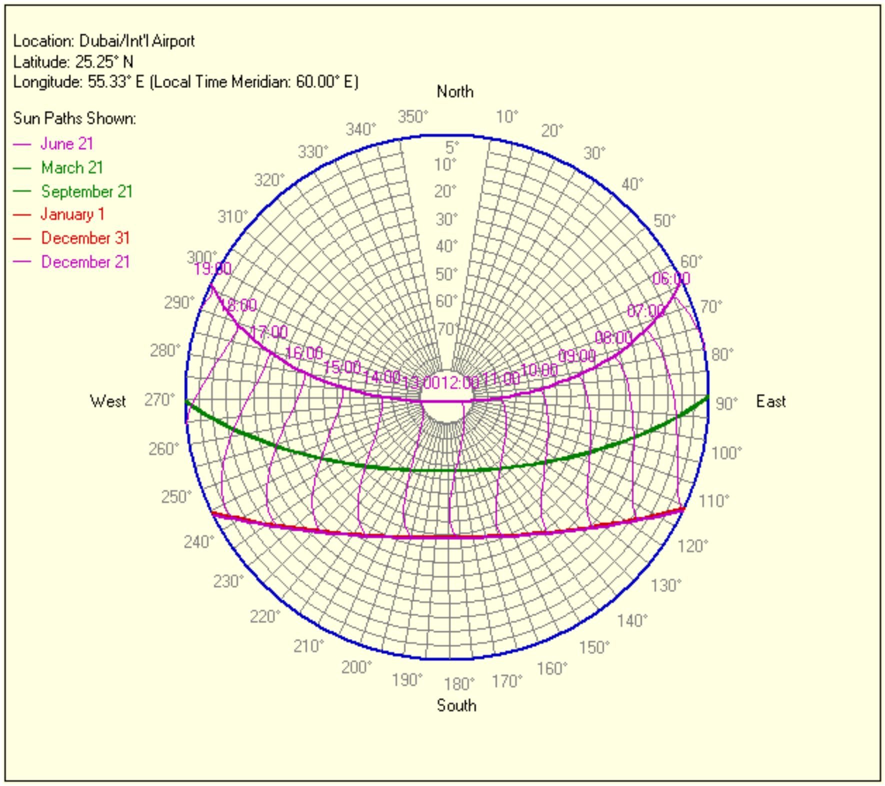


Figure 62. Sun path- Dubai (IES)

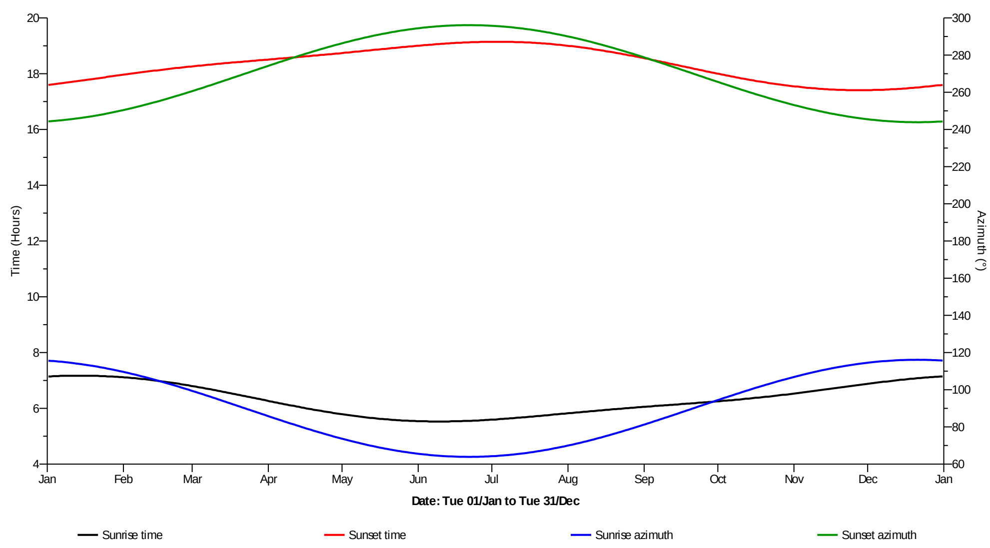


Figure 63. Sunset and sunrise times and azimuth- Dubai (IES)

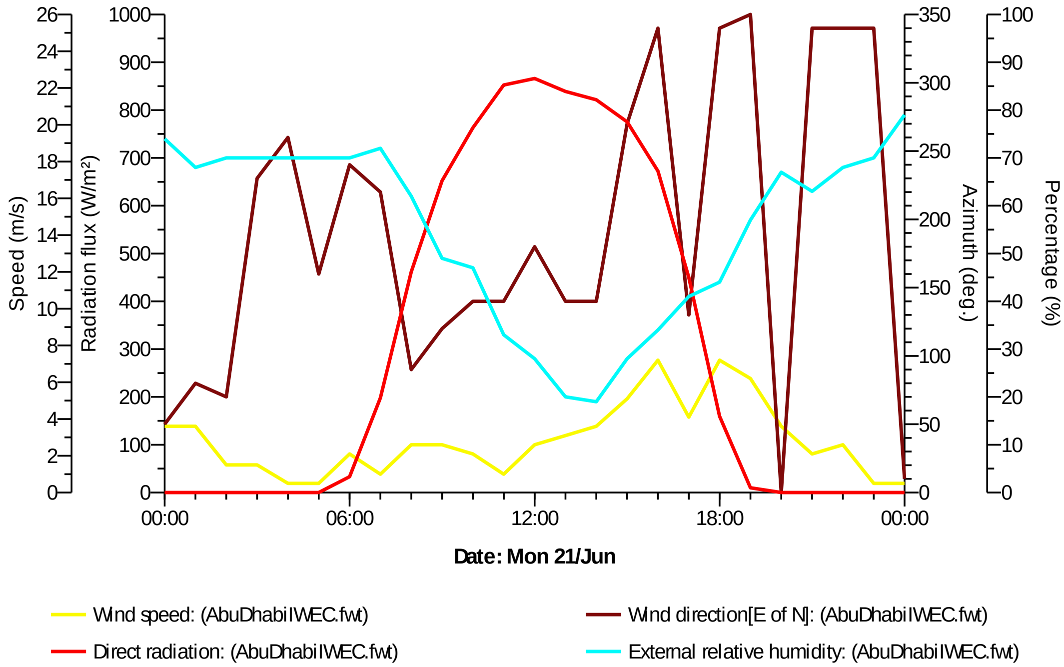


Figure 64. Wind speed, wind direction, direct radiation and relative humidity on the summer solstice- June. 21- Dubai (IES)

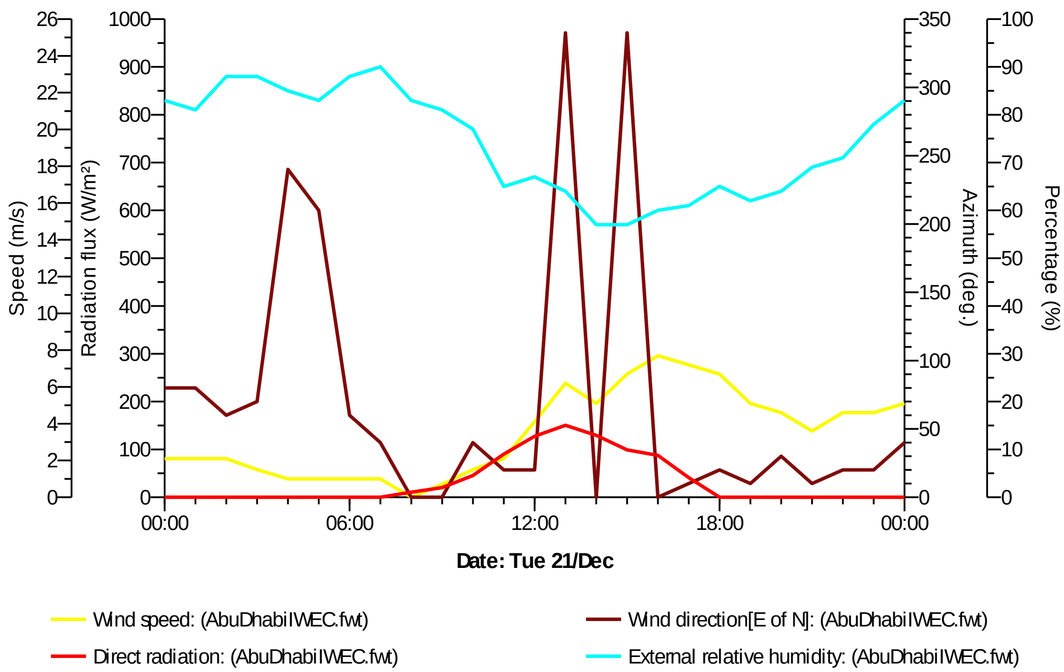


Figure 65. Wind speed, wind direction, direct radiation and relative humidity on the winter solstice- December. 21- Dubai (IES)

Figure 61 shows the monthly maximum dry-bulb and wet-bulb temperatures. The wet-bulb temperatures are similar to the data represented earlier in section 4.1. However, according to the graph, the temperature reaches the highest peak in July at 44 ° C, and the lowest on January at 28 °C.

Figures 62 and 63 are provided by SunCast module. They represent the sun path diagram during the months from January to December, in which the sun becomes higher during summer and lower during winter. Additionally, the latter shows the sunrise and sunset times and azimuth in Dubai city.

Figures 64 and 65 are based on Abu Dhabi Weather File as the nearest available to the site (Dubai) based on Simulation Weather Data of APLoacte. These figures represent summer and winter solstice days (June 21 and December 21) are represented with regard to the wind speed, wind direction, solar radiation and relative humidity. It is observed that on both days that the solar radiation increase boosts up the wind speed with a four to six hour lag in the peak times. The prevailing wind direction is north (360 degree on the right vertical axis) starting sometime between 12PM and 1PM on the selected dates. Additionally, the relative humidity reaches the highest percentages early in the morning and late at night.

Figure 66 and 67 show the prevailing wind for the study models on December 21, which comes from the north and northeast with a speed ranging from 3-9 m/s.

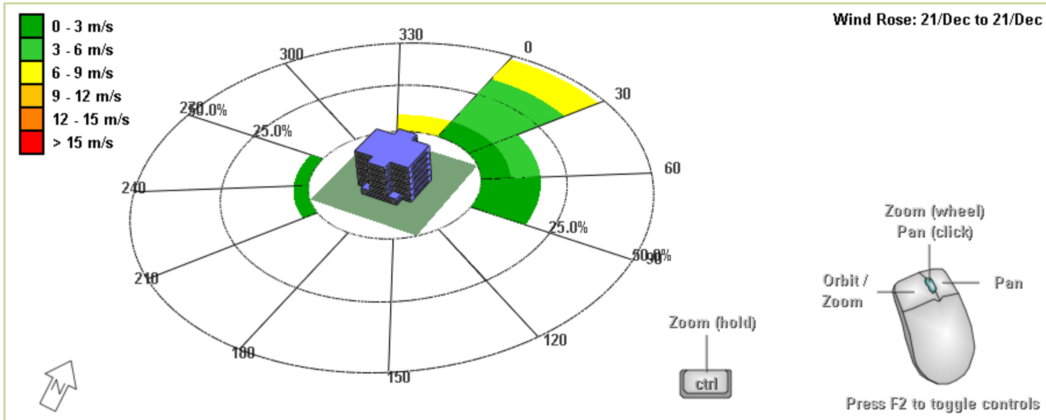


Figure 66. Wind Rose, conventional model, Dec. 21 (IES)

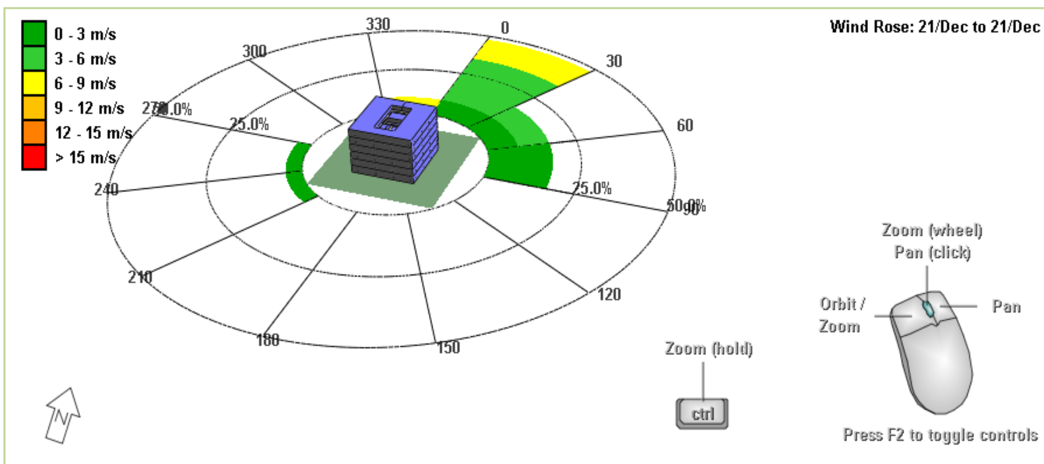


Figure 67. Wind Rose, courtyard model, Dec. 21 (IES)

4.4.2. Models

Based on the previously described proposal, two forms are generated via ModelIt module in IES Software: the conventional and the courtyard models. General and close-up views for both models are shown in Figs. 68 and 69.

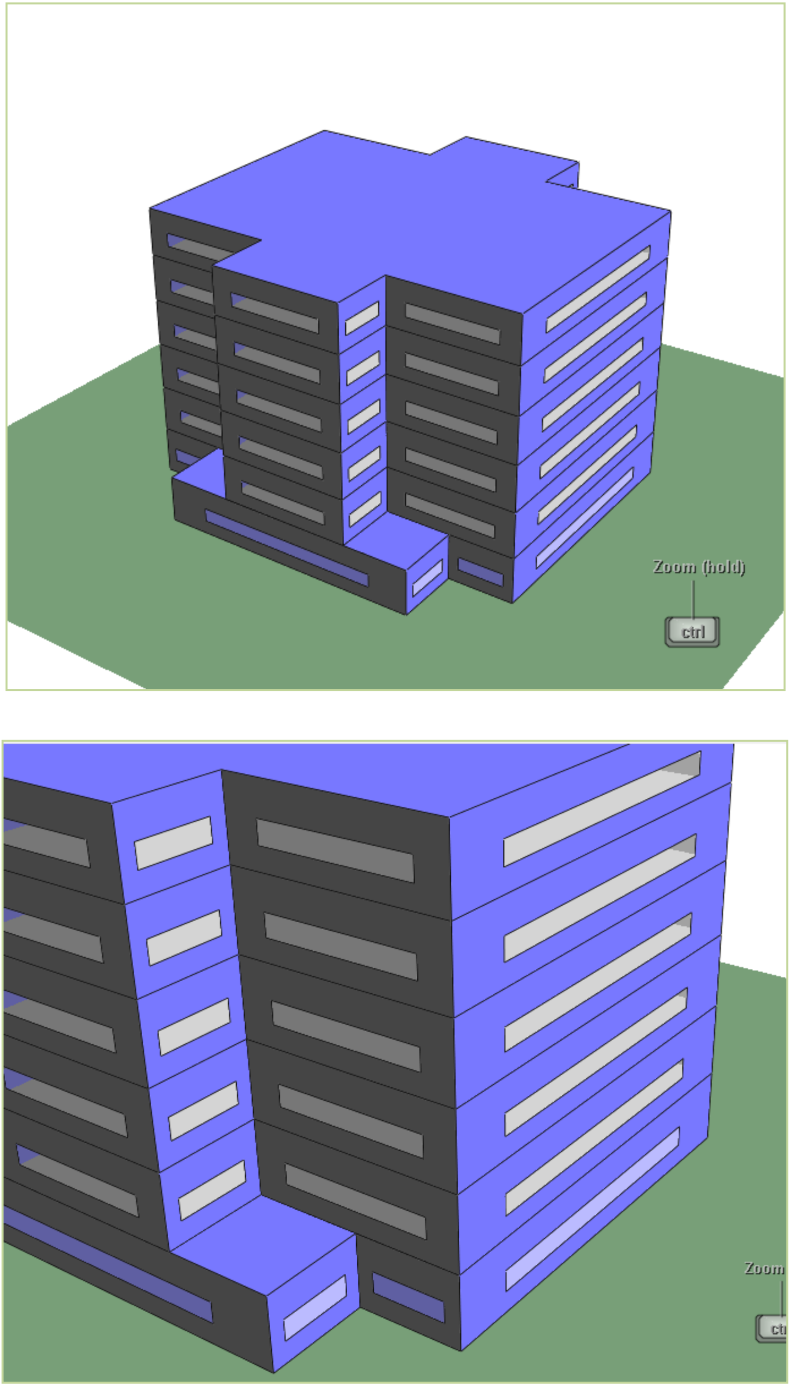


Figure 68. The conventional model (IES)

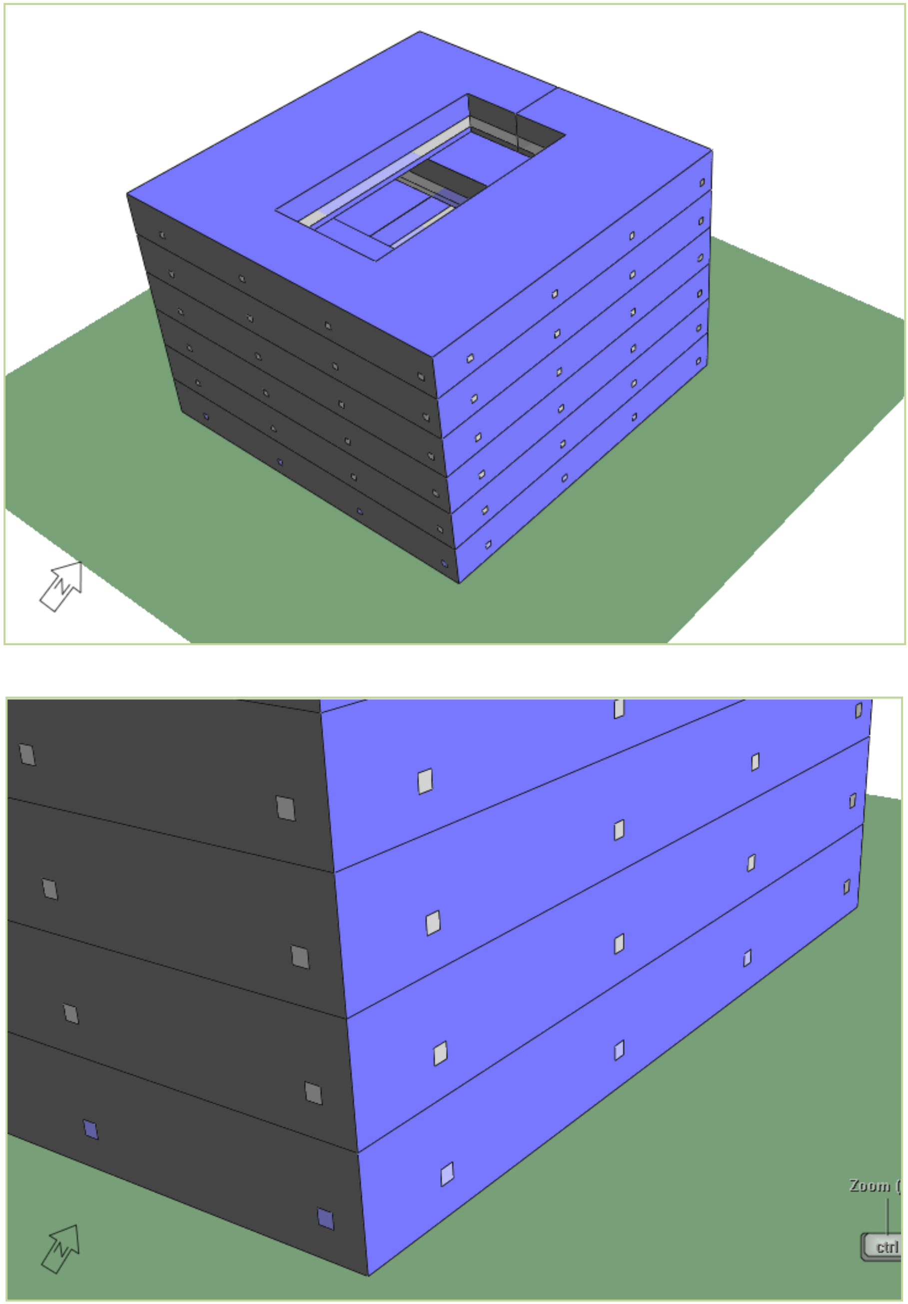


Figure 69. The courtyard model (IES)

4.4.3. Construction Materials

The software offers wide range of construction materials categorized into Opaque and Glazed materials. The Opaque ones include: roof, ceiling, external wall, internal partition, ground floor and door, whereas the Glazed materials include rooflight, external glazing and internal glazing. The construction materials of the studied models are set to the software default from the Apache Construction Database through the Building Template Manager, as shown in Fig. 70 below. Figure 71 shows the external walls construction layers (listed from outside to inside) as well as their properties: thickness, conductivity, density, heat capacity and category, as this reaserach is mostly concerned with the external walls properties in the second step. In the reference model, the insulation material is set to Dense EPS Slap Insulation of 5.0 cm thickness and the wall thickness is 25 cm, as explained earlier in Tables 6 and 9.

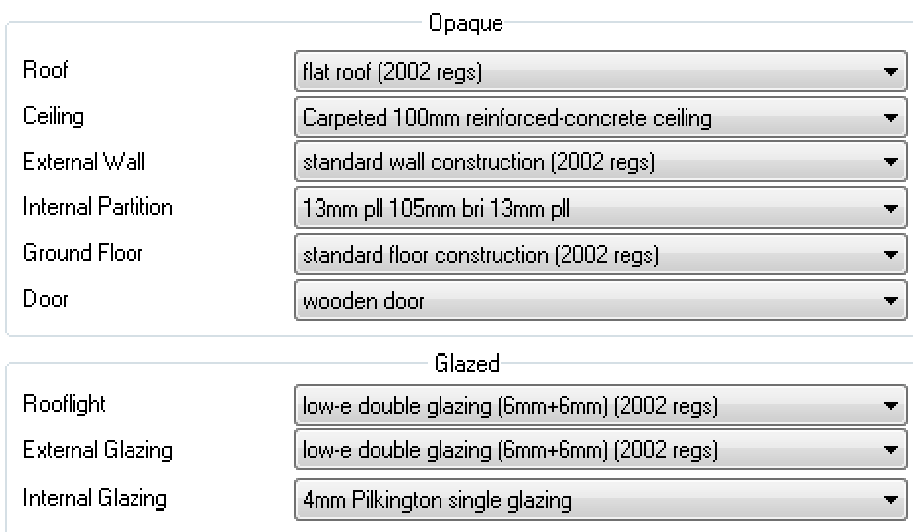


Figure 70. The construction materials as per Apache Construction Database (IES)

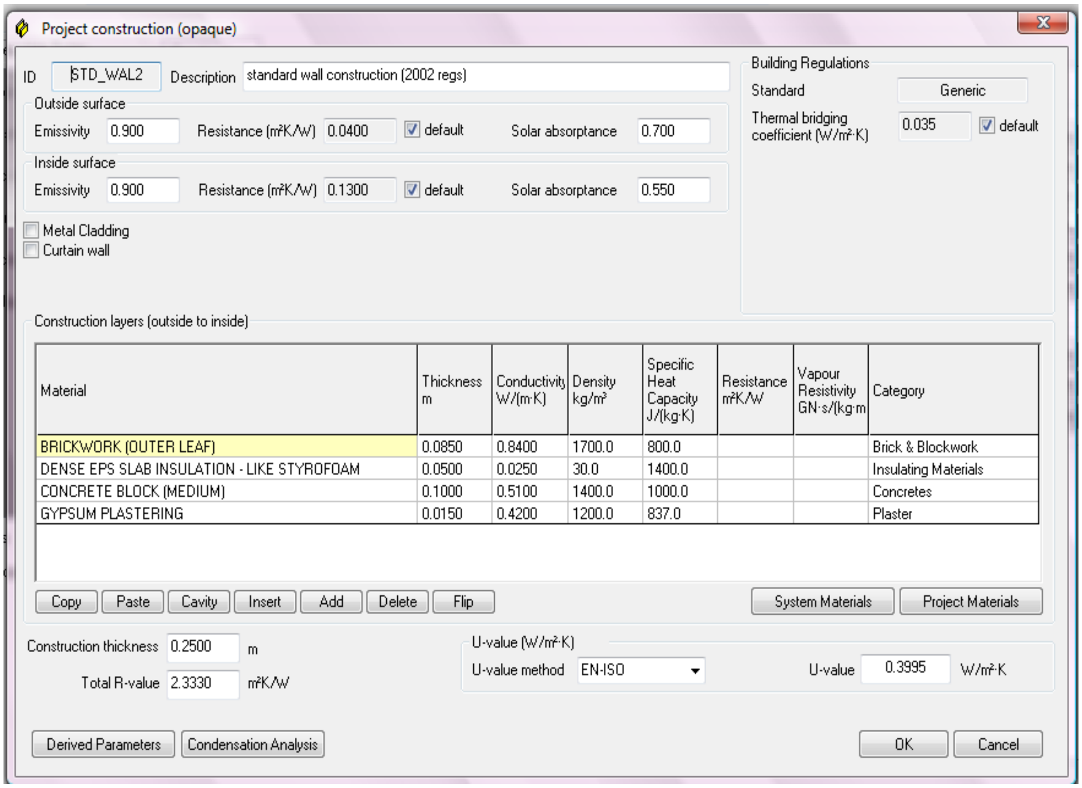


Figure 71. The external wall construction materials of the models (IES)

4.4.4. Areas Calculations

Based on IES software calculations in the ModelIt Module, Table 11 summarizes the figures related to the total volume, floor area, external wall area and external opening area. However, the conventional and courtyard forms have equal volume and total floor area, whereas the external wall areas in the courtyard form is 47.2% larger than in the conventional form. On the other hand, the external opening area is equal in both forms, though it constitutes different percentages with respect to the external wall areaa, which is 14% in the courtyard form and 20% in the conventional form (Figs. 68 and 69).

Table 11. Areas details of the study models as per IES calculations

	Volume (m^3)	Floor area (m^2)	External Wall Area (m^2)	External Opening Area (m^2)
Courtyard	15050	4300	3710	504 (14%)
Conventional	15050	4300	2520	504 (20%)

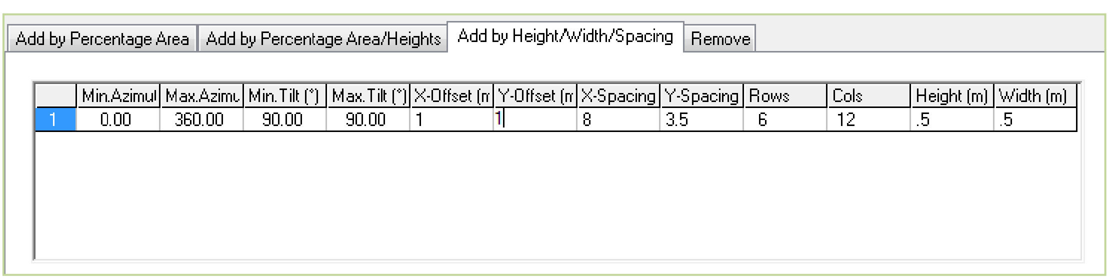
4.4.5. Windows Configuration

The window configuration in the courtyard model is based on the following assumptions:

- The courtyard model is mostly opened facing inside, while the outside walls have minimal openings in terms of area and size to maintain privacy and avoid high solar glare as per previously presented literature review.
- Windows on outside walls are further smaller compared to the same on inside walls in order to avoid sun glare and enhance cross ventilation effect through the internal spaces, as per Fig. 40.
- An equal glazing area is applied for both conventional and the courtyard models. This area constitutes slightly different percentages in each as it is based on the literature review: the courtyard housing enjoys fewer openings in general, especially to the outside, while the conventional housing blocks are entirely opened to the outside.
- The daylight in the courtyard model is penetrating from two sides, rather than one side in the conventional. This explains the assumed need for less opening size in the courtyard model.

In view of above assumptions, openings are designed as described in the following:

- The inside windows in courtyard model are 1.0 m long and 0.5 m high form the slab.
- The outside windows in courtyard model are 0.5 x 0.5 m and 1.0 m high from the slab, as shown in Fig. 72.
- The windows in conventional model are 1.0 m long, 1.0 m high from slab, whereas the width is varied based on 20% glazing area all around the model, as shown in Fig. 73.
- The opening types as defined by MacroFlo are (this applies on both forms, Fig. 74):
    - Opening threshold temperature is 25 °C: the openings close automatically when the outside temperature is higher than 25° C, and open automatically when the outside temperature is lower, in order to facilitate a natural ventilation effect based on comfortable temperature degree.
    - Degree of opening: ON: Continuously: this applies only when outside temperature is equal to the opening threshold temperature or lower.
    - Operable Area is 10% of opening area: this applies only when outside temperature is equal to the opening threshold temperature or lower.



	Min.Azimut	Max.Azimu	Min.Tilt (°)	Max.Tilt (°)	X-Offset (m	Y-Offset (m	X-Spacing	Y-Spacing	Rows	Cols	Height (m)	Width (m)
1	0.00	360.00	90.00	90.00	1	1	8	3.5	6	12	.5	.5

Figure 72. The outside windows in the courtyard form (height, width and spacing) as per MacroFlo Openings Type (IES)

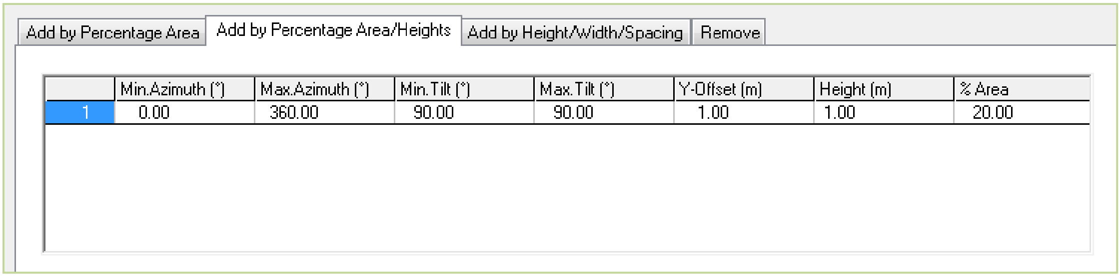


Figure 73. The outside windows in the conventional form (percentage area and height) as per MacroFlo Openings Type (IES)

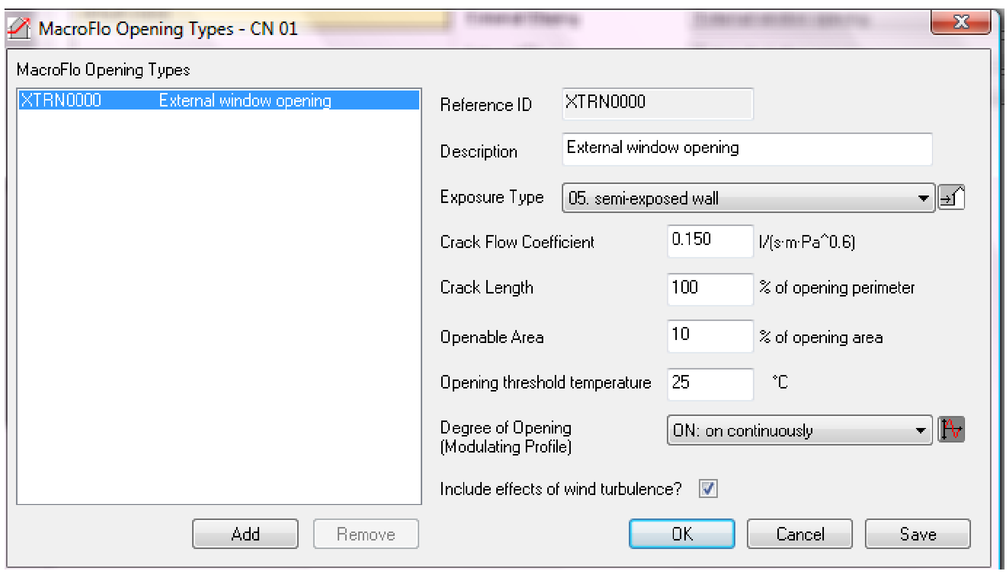


Figure 74. The openings types controls in the two forms as per MacroFlo Openings Type (IES)

Chapter 5: Results and Discussion

5.1. Step 1: Conventional Form versus Courtyard Form

1. ***Thermal Simulation***

Simulation by ApacheSim for this step is run in two different methods in order to validate the results. The first method is based on two runs for winter and summer, whereas the second method is one run for the whole year, based on the temperature threshold, which controls the opening/closing process of the windows based on a specific preset temperature, thus alleviating the need to do separate runs for winter and summer. Furthermore, the temperature threshold is also applied in the winter run. As in real buildings the openings could be controlled manually by occupants depending on the outside temperature. In the winter simulation, the windows close automatically if the outside temperature is higher than 25ºC. The results from both methods were extremely close (monthly breakdowns for the two methods are attached in Appendices A, B and C). Table 12 summarizes the results given by ApachSim's runs for both forms:

Table 12. Simulation results by ApachSim- Fisrt step

	Solar Gain (MWh)	External Conduction Gain (MWh)	Total Energy (MWh)
Conventional	211.41	88.89	465.84
Courtyard	96.73	137.02	433.67

These measures are defined as per IES Software as per the following:

Solar gain: Solar radiation absorbed on the internal surfaces of the room, and solar radiation absorbed in glazing and transferred to the room by conduction.

External conduction gain: Heat conducted into (or if negative, out of) the room through the internal surfaces of externally exposed elements, including ground floors.

Total energy: Total energy consumption for systems, lights and small power, includes a negative contribution from any electricity generated by PV, wind turbine and CHP systems. For the aim of this study, heating, lighting and equipment energy are set to zero, as they are not being controlled in the models. Thus, the total energy represents cooling loads only.

Figure 75 shows a comparison between the conventional and courtyard forms with respect to solar gain. The readings show 54.24% reduction in the courtyard form. This can be explained because most openings in the courtyard form are shaded and located in the controlled microclimate of the courtyard space, compared to the conventional ones. Therefore, less heat gain is revealed in the courtyard form.

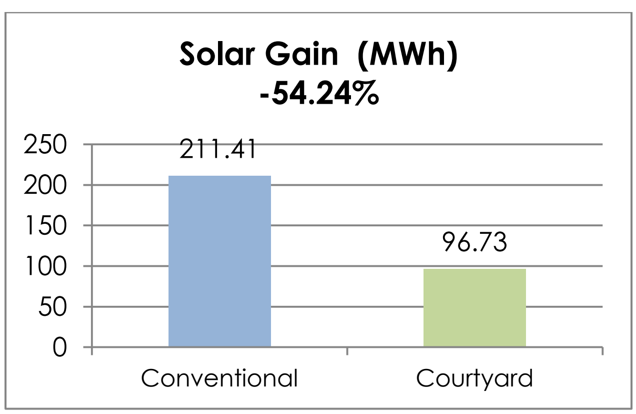


Figure 75. Solar gain in conventional and courtyard forms

As for the external conduction gain, the courtyard form shows 54.14% increase compared to the conventional form (Fig. 76) due to the larger area of external surfaces (walls and floors) in the courtyard form. As presented earlier, Table 11 shows 47.2% higher external walls in the courtyard form than the conventional. Therefore, the heat transfer is higher due to the large external exposure in the courtyard model. However, it is noticed also that the conduction gain percentage is higher than the external wall percentage. This is due to the presence of added external surfaces represented in the rotated floors in the courtyard space, Fig. 69.

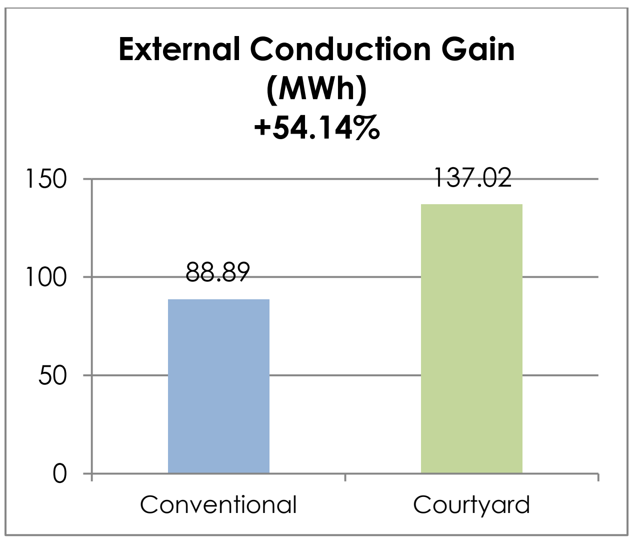


Figure 76. External conduction gain in conventional and courtyard forms

The total energy consumption graph (Fig. 77) shows a reduction of 6.90% in the courtyard form as a result of the sum of less cooling load components. However, and as mentioned earlier, the total energy consumption is limited to the cooling loads as it excludes heating, systems, lights and small power. This is further affected by the total solar and external conduction gains. Even though the external conduction gain in the courtyard is 54.14% higher than the same in the conventional, the less solar gain (54.24%) in the courtyard form seems to be more dominant in the overall cooling effect.

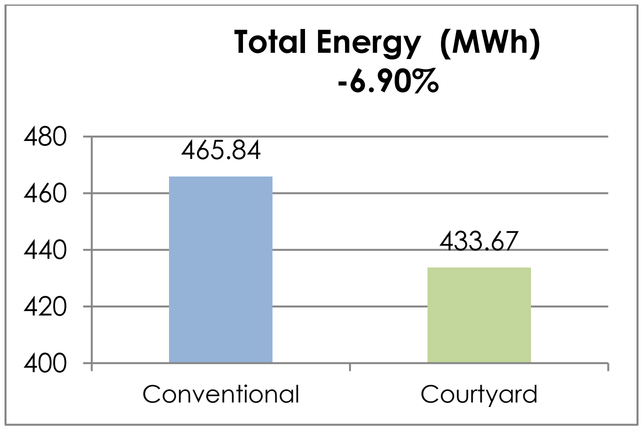


Figure 77. Total energy in conventional and courtyard forms

Figure 78 shows the monthly breakdown of energy consumption of the conventional and courtyard models. The energy performance of the models conforms largely in the hottest months of June, July and August. While the rest of the year shows a significant distinction in energy performance, which influences the overall energy scenario.

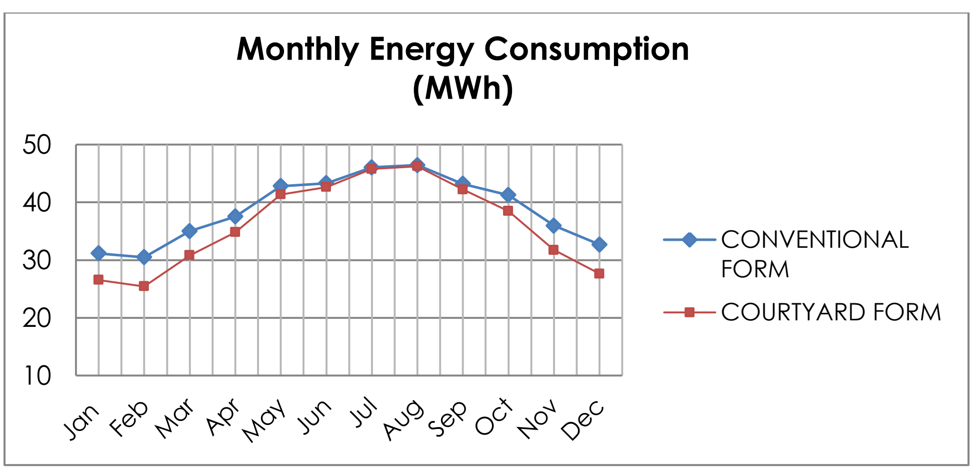


Figure 78. Monthly energy consumption of conventional and courtyard model

This behavior in the hot months can be explained based on Muhaisen's conclusion (2005) that despite the shading effect on the reduction of cooling needs in summer generally, high sun altitude results in considerably less shaded area as in Cairo, Table 3. While places with lower sun altitude become more responsive by increased shaded areas during summer. Additionally, the higher conduction gain of the courtyard model in summer affects its energy performance, as more cooling loads will be needed.

2. Solar Shading Calculations

Unwanted Solar gain is a major contributor towards unnecessary building energy consumption, particularly in hot climates. The solar radiation is visualized on the forms using SunCast module in IES Software. Then the solar shading calculation is fed into the thermal simulation to determine the impact of heating and cooling energy as explained in the previous section. Figure 79 shows that the highest solar radiation is received from April to September between 11:00 and 14:00 hours, whereas less than 50% of the model surfaces are exposed to the intense solar radiation in the months of January, February, November and December. These calculations apply on the conventional and courtyard models in the given climate of Dubai.

Month	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan	-	-	-	-	-	-	-	10.06	21.36	31.23	38.81	42.99	42.83	38.39	30.62	20.63	9.26	-	-	-
Feb	-	-	-	-	-	-	0.25	13.13	25.33	36.34	45.26	50.61	50.91	46.04	37.43	26.59	14.49	1.67	-	-
Mar	-	-	-	-	-	-	5.94	19.31	32.28	44.40	54.69	61.10	60.90	54.20	43.76	31.58	18.58	5.19	-	-
Apr	-	-	-	-	-	-	13.23	26.79	40.28	53.43	65.46	73.54	71.39	61.24	48.64	35.31	21.77	8.24	-	-
May	-	-	-	-	-	4.68	17.74	31.09	44.60	58.16	71.50	82.67	77.73	64.85	51.35	37.80	24.35	11.13	-	-
Jun	-	-	-	-	-	5.76	18.48	31.56	44.89	58.37	71.93	85.27	80.44	66.92	53.38	39.94	26.69	13.73	1.19	-
Jul	-	-	-	-	-	3.87	16.68	29.85	43.25	56.78	70.32	83.29	81.00	67.76	54.20	40.69	27.32	14.21	1.49	-
Aug	-	-	-	-	-	0.83	14.11	27.59	41.15	54.59	67.43	77.35	75.58	64.45	51.38	37.89	24.33	10.88	-	-
Sep	-	-	-	-	-	-	11.57	25.04	38.19	50.56	61.03	66.76	64.34	55.45	43.69	30.80	17.43	3.89	-	-
Oct	-	-	-	-	-	-	8.38	21.24	33.31	43.94	51.86	55.14	52.55	45.10	34.72	22.78	10.00	-	-	-
Nov	-	-	-	-	-	-	3.84	15.93	26.99	36.34	42.96	45.59	43.56	37.39	28.33	17.46	5.47	-	-	-
Dec	-	-	-	-	-	-	-	11.47	22.27	31.46	38.14	41.28	40.20	35.14	27.07	16.97	5.59	-	-	-

Figure 79. Solar calculations by SunCast in percentage of surface area (%) (IES)

A series of images have been created by SunCast to visualize where the shadows are cast onto the models surfaces at specific times of the year. These dates are on 21st of March, 21st of June, 21st of September and 21st of December; at 12:00, 14:00 and 16:00 hours.

Figure 80 shows shadow casting on the conventional model, it reveals that the building is largely exposed to summer sun especially in June at noon (1200 hours), when the sun is at a high altitude and the need for shade is more valued. In the courtyard model, the external envelope (excluding the courtyard walls) is similarly exposed to the summer sun, while the courtyard walls are exposed to a controlled climate inside the courtyard (reduced temperature). Therefore, the solar heat gain is reduced which may lead to a lower cooling loads in summer, Fig. 81.

On the other hand, the courtyard model represents the importance of the internal void in attracting the winter sun into the building (in September and December). Hence, increasing the surface area exposed to the solar heat gain which leads to a lower heating loads in winter (if any needed).

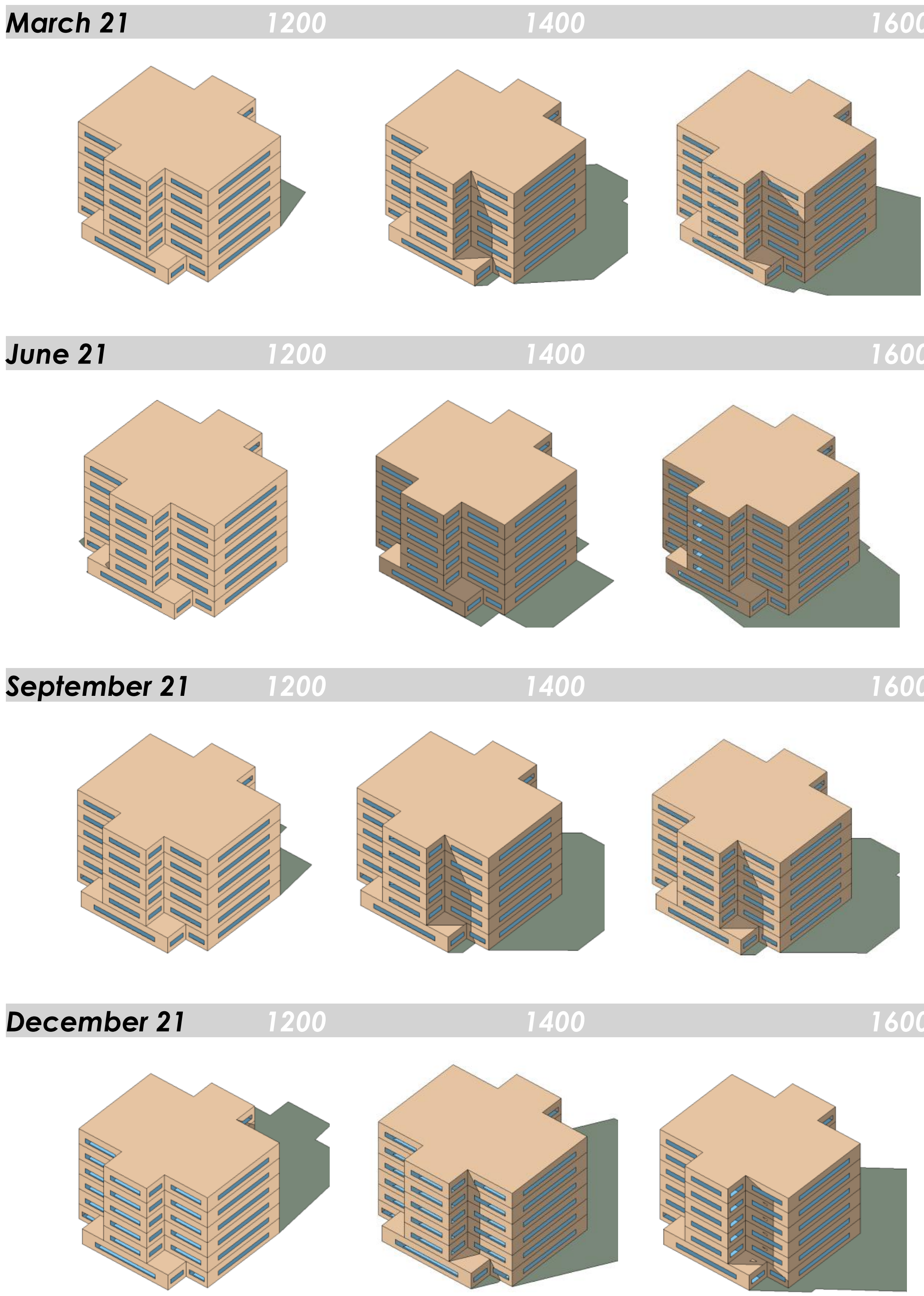


Figure 80. Shading analysis of conventional model (IES)

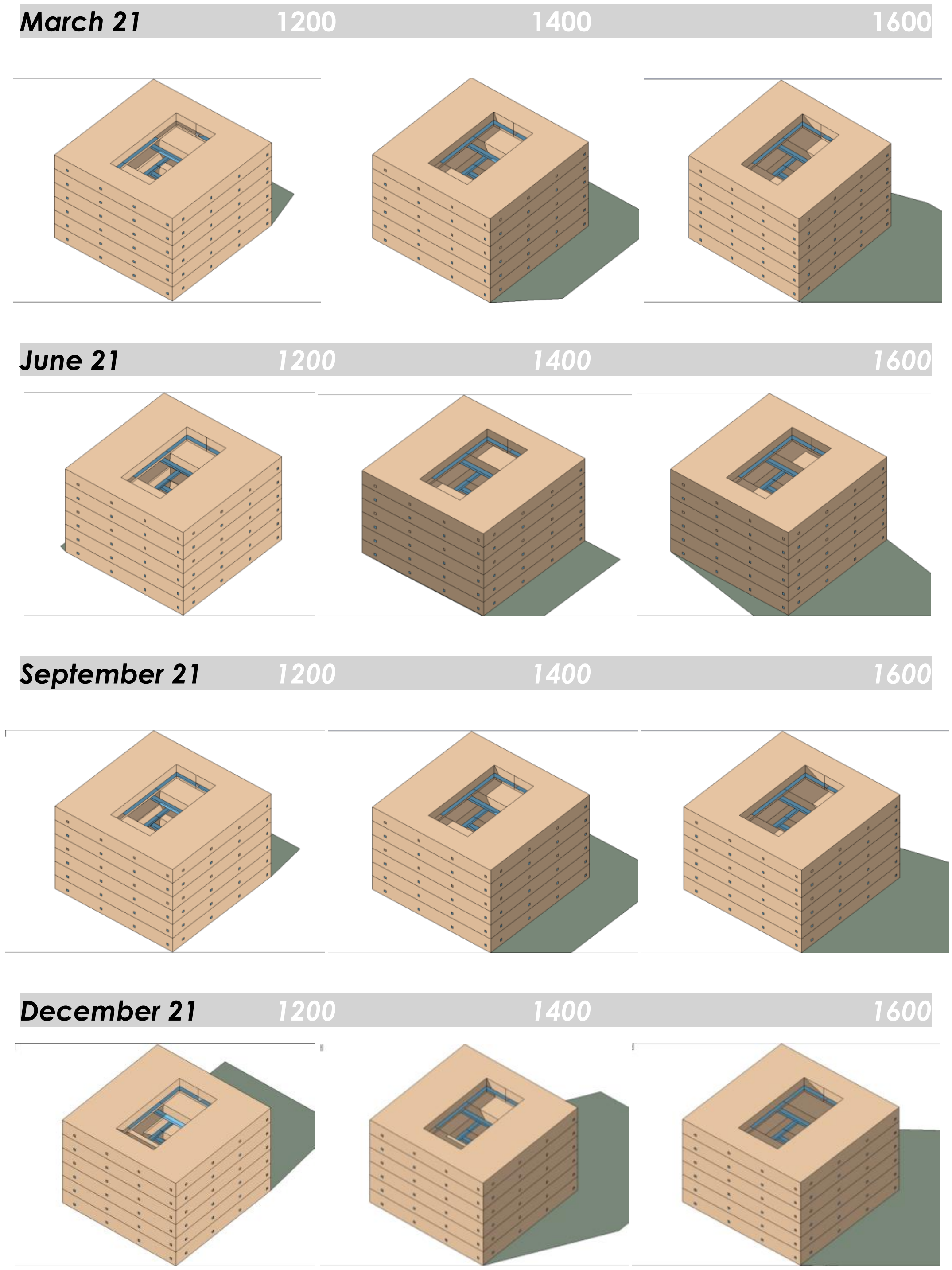


Figure 81. Shading analysis of courtyard model (IES)

3. Daylight Analysis

Daylighting is a key measurement of efficient energy performance, as well as occupants comfort. Daylight is the combination of all direct and indirect sunlight outdoors during the daytime. Kwok defines the Daylight Factor (DF) as a numerical ratio that describes the relationship between indoor and outdoor light illuminance (2007, p. 57).

The daylight is affected by many factors such as opening size and location, room geometry, transmittance of glazing and reflectance of exterior and interior surfaces. Daylight illuminance (lux) is calculated in relation to daylight factor as follows:

$$\boldsymbol{Daylight\ Illuminance} = (\boldsymbol{DF\ at\ point\ A})(\boldsymbol{exterior\ illuminance}) \qquad (5)$$

The US Green Building council recommends a minimum DF of 2% for 75% of occupied spaces as a requirement for the LEED daylighting credit. Moreover, Rooms with less than 2% DF look gloomy, which requires electrical lighting. Rooms with DF between 2% and 5% are adequately daylit, though some electrical lighting might be needed, whereas a DF greater than 5% makes the room strongly daylit (Kwok et al 2007, p. 60).

The illuminance and daylight factors are calculated in the conventional and courtyard models by FlucsDL, IES Software. The results represent the values of daylight as numerical and graphic outputs. Two daylighting scenarios are selected based on the Solar Shading Calculations performed earlier (Fig. 82). The two days represent low and high solar radiations received by models surfaces on solstice days: December 21st at 4:00 PM (solar shading 16.67%) and June 21st at 12:00 PM (the highest solar shading 85.27%). The selected dates represent the two extremes throughout the whole year.

Figures 82 and 83 show daylight level and daylight factors for the conventional model on December 21 at 4:00 PM. Table 13 summarizes the results showing that average DF is 14.5% and average daylight level is 908.22 lux.

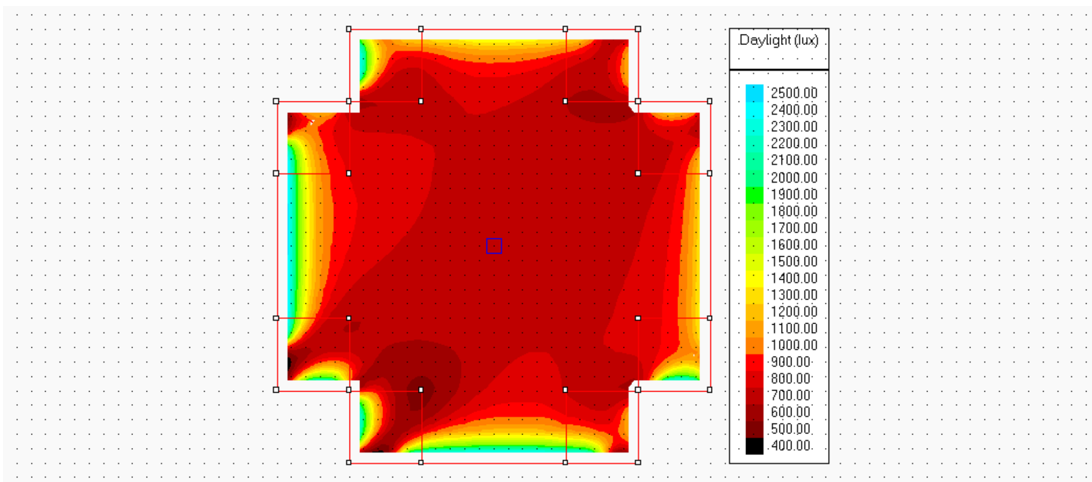


Figure 82. Daylight levels (lux) in conventional model, Decemebr 21, 4:00 PM (IES)

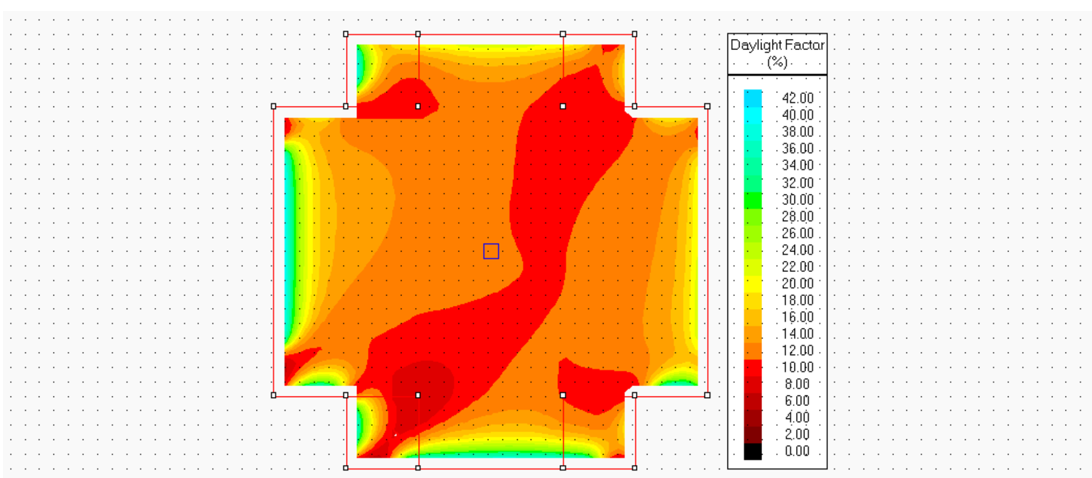


Figure 83. Daylight factor (%) in conventional model, December 21, 4:00 PM (IES)

Table 13. Summary of results for daylight in the conventional model by FlucsDL, December 21, 4:00 PM

Surface	Quantity	Values			Uniformity	Diversity
		Min.	Ave.	Max.	(Min./Ave.)	(Min./Max.)
Working plane 1 Reflectance=0% Transmittance=100% Grid size=0.50 m Area=741.000 m² Margin=0.50 m	**Daylight factor**	7.1 %	14.5 %	40.1 %	0.49	0.18
	Daylight illuminance	441.03 lux	908.22 lux	2503.23 lux	0.49	0.18

Figures 84 and 85 show daylight level and daylight factors for the courtyard model on the same date and time. Table 14 shows that average DF is 6.3% and average daylight level is 396.28 lux.

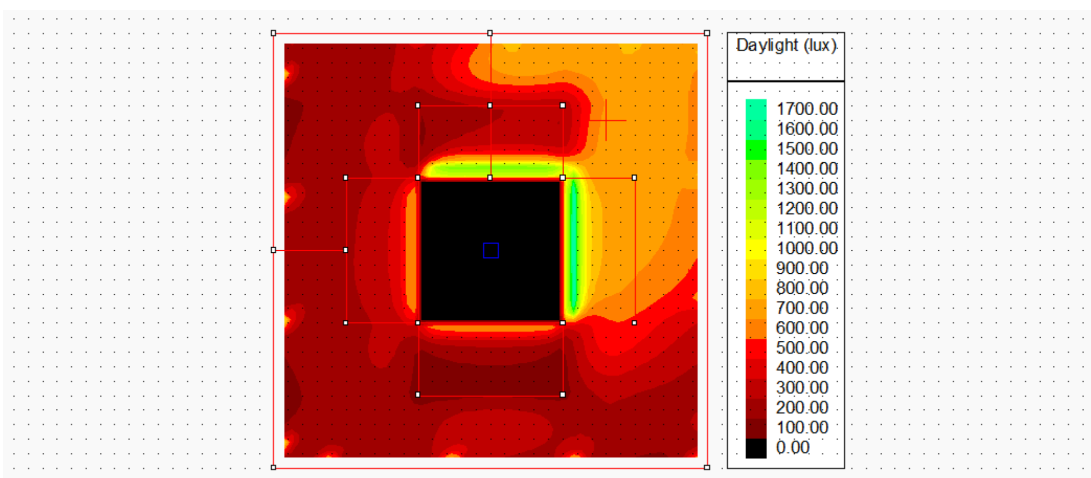


Figure 84. Daylight levels (lux) in courtyard model, December 21, 4:00 PM (IES)

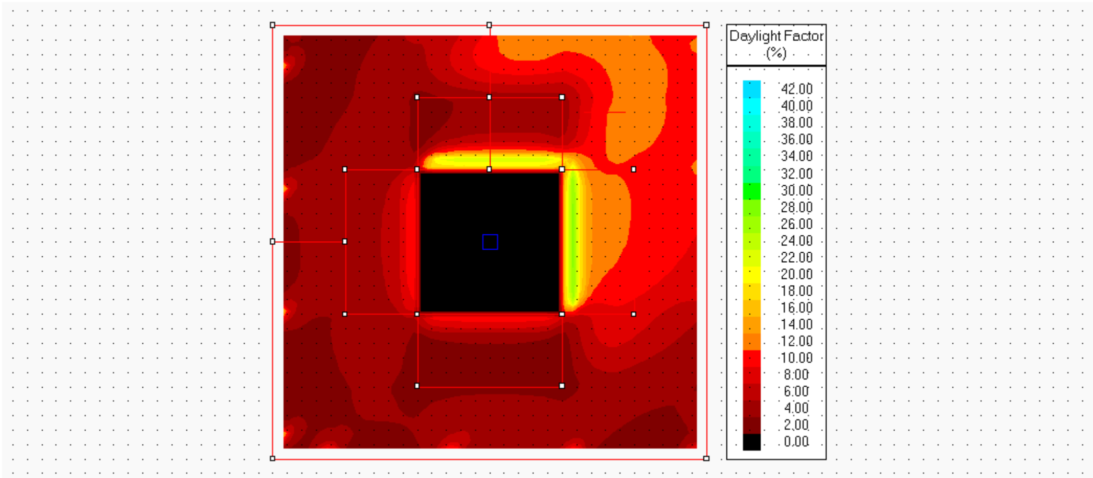


Figure 85. Daylight factor (%) in courtyard model, December 21, 4:00 PM (IES)

Table 14. Summary of results for daylight in the courtyard model by FlucsDL, December 21, 4:00 PM

Surface	Quantity	Values			Uniformity	Diversity
		Min.	Ave.	Max.	(Min./Ave.)	(Min./Max.)
Working plane 1 Reflectance=0% Transmittance=100% Grid size=0.50 m Area=841.000 m² Margin=0.50 m	**Daylight factor**	0.5 %	6.3 %	28.1 %	0.08	0.02
	Daylight illuminance	31.30 lux	396.28 lux	1753.75 lux	0.08	0.02

As for the summer day, Figures 86 and 87 below show daylight level and daylight factors for the conventional model on June 21 at 12:00 PM. Table 15 shows that average DF is 10.1% and average daylight level is 2509.47 lux.

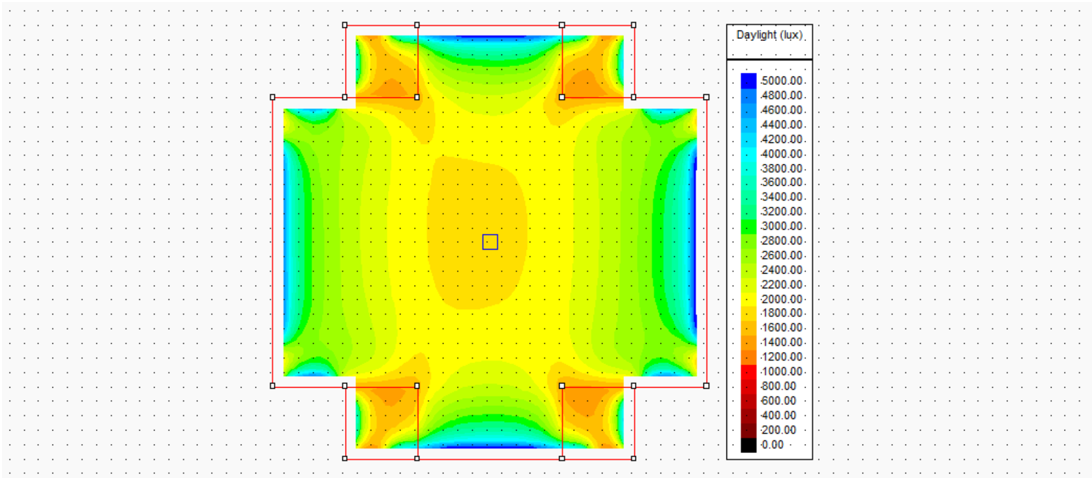


Figure 86. Daylight levels (lux) in conventional model, June 21, 12:00 PM (IES)

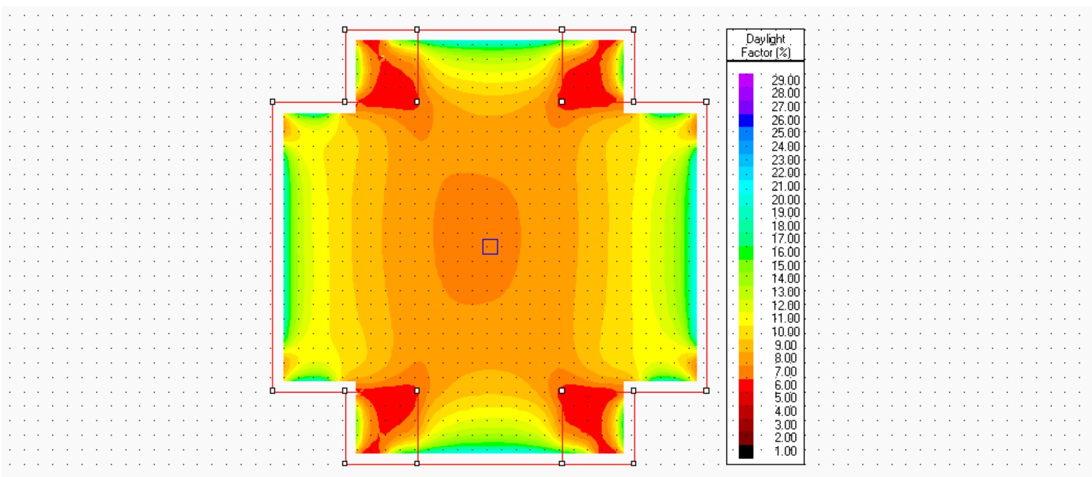


Figure 87. Daylight factor (%) in conventional model, June 21, 12:00 PM (IES)

Table 15. Summary of results for daylight in the conventional model by FlucsDL, June 21, 12:00 PM

Surface	Quantity	Values			Uniformity	Diversity
		Min.	Ave.	Max.	(Min./Ave.)	(Min./Max.)
Working plane 1 Reflectance=0% Transmittance=100% Grid size=0.50 m Area=741.000 m² Margin=0.50 m	**Daylight factor**	6.3 %	10.1 %	21.6 %	0.62	0.29
	Daylight illuminance	1553.16 lux	2509.47 lux	5351.84 lux	0.62	0.29

Figures 88 and 89 show daylight levels and daylight factors for the courtyard model on the same date and time. Table 16 shows that average DF is 5.6% and average daylight level is 1394.65 lux.

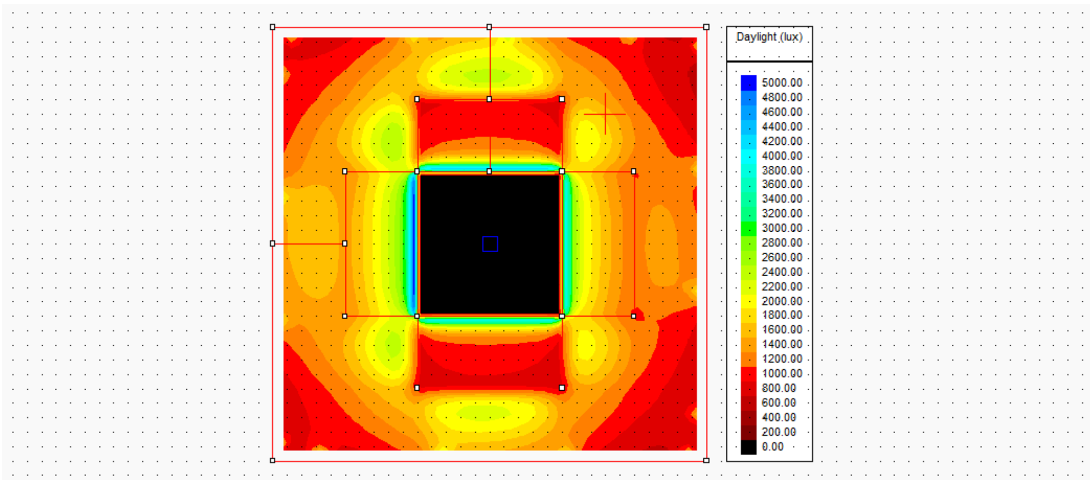


Figure 88. Daylight levels (lux) in courtyard model, June 21, 12:00 PM (IES)

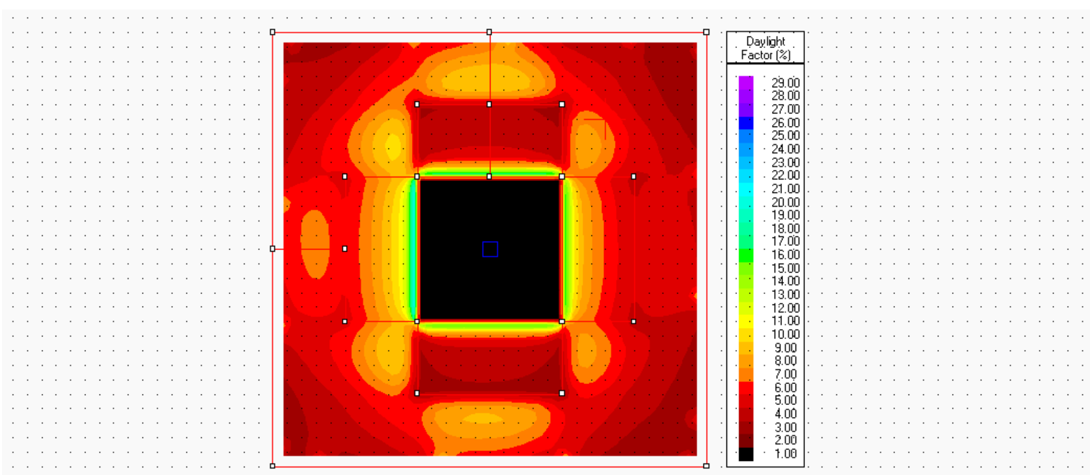


Figure 89. Daylight factor (%) in courtyard model, June 21, 12:00 PM (IES)

Table 16. Summary of results for daylight in the courtyard model by FlucsDL, June 21, 12:00 PM

Surface	Quantity	Values			Uniformity (Min./Ave.)	Diversity (Min./Max.)
		Min.	Ave.	Max.		
Working plane 1 Reflectance=0% Transmittance=100% Grid size=0.50 m Area=841.000m² Margin=0.50 m	**Daylight factor**	0.3 %	5.6 %	20.3 %	0.05	0.02
	Daylight illuminance	76.35 lux	1394.65 lux	5024.25 lux	0.05	0.02

The above results show that the courtyard model performs better in terms of daylighting on both winter and summer days, which means less glare into the interiors than the conventional form. In addition, the average daylight factors of 6.3% and 5.6%, for the winter and summer days, respectively, are close to the USGBC recommended daylight factor level of 5%, which means that the courtyard form requires less usage of passive strategies such as shading devices and light shelves.

Table 17, Figs. 90 and 91 below draw a comparison between the conventional and courtyard models in daylight performance with respect to the recommended DF on the selected days.

Table 17. Summary of DF on winter and summer days compared to the recommended in the conventional and courtyard models

	Conventional	Courtyard	Recommended
DF on Dec. 21st	14.5%	6.3%	5%
DF on Jun. 21st	10.1%	5.6%	5%

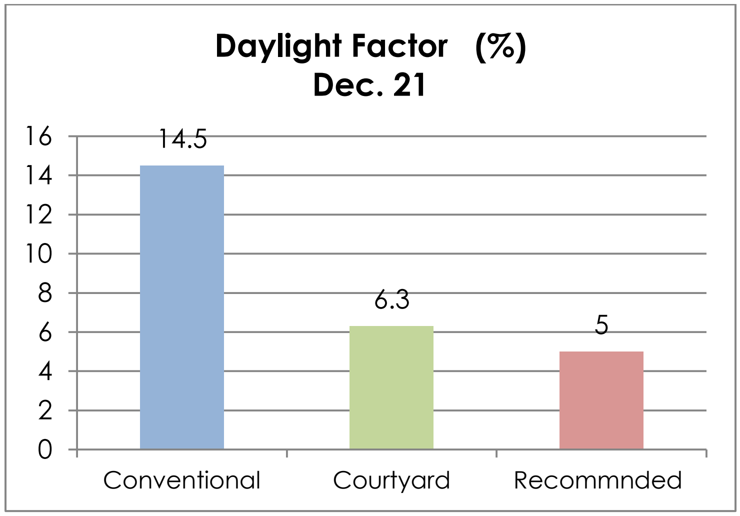


Figure 90. Daylight factors in both models compared to recommended- Dec. 21

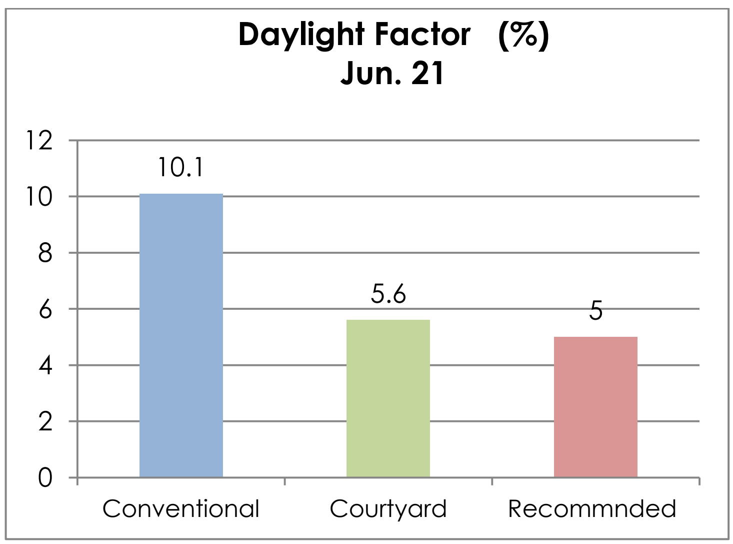


Figure 91. Daylight factors in both models compared to recommended- Jun. 21

4. Air Movement Analysis

When air hits a building surface, pressure is created. This pressure will be higher than the outside pressure. If there are openings on the windward side of the building, the pressure differential between the wind and the building interior will cause outside air to pass in through the openings, producing air flow within the building, and this is what is called cross ventilation.

A CFD analysis by MicroFlo, IES is run to compare the behavior of external airflow in the conventional versus the courtyard model. "The CFD analysis refers to numerical simulation of the fluid motion, typically air, in a space, to predict the performance of natural ventilation and active air systems" (Kwok et al 2007, p. 338). This simulation is based on IES recommendations, to apply a grid where the top boundary is 5 h away from the building, where h is the building height, and the outflow boundary is 15 h behind to allow for air development and prevent an artificial acceleration of the flow over the building. The sides are set to 3-5 h. Figure 92 shows the velocity contours plotted on the CFD grid around the conventional model. The blue color stands for less velocity and temperature, whereas the red stands for higher velocity and temperature.

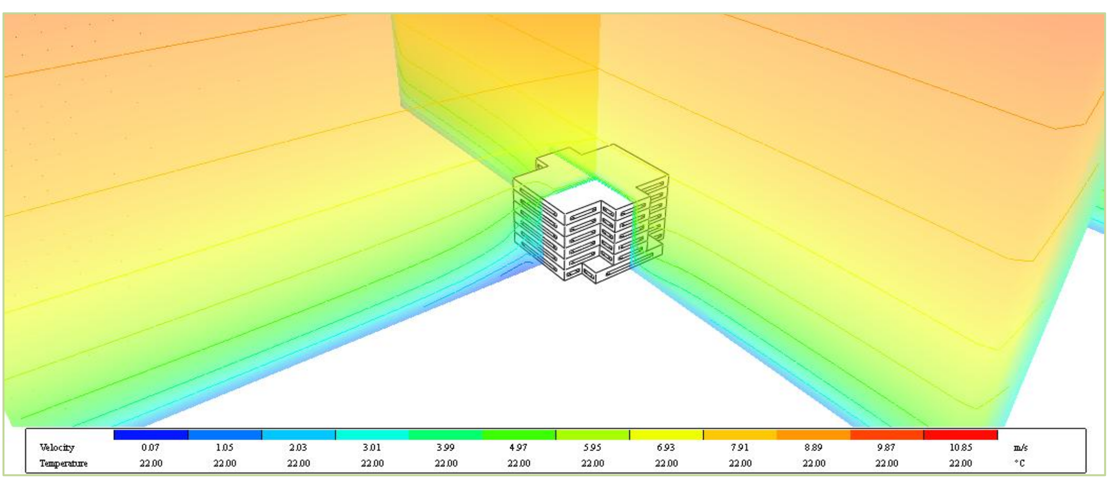


Figure 92. CFD Analysis of the conventional model, Dec. 21 (IES)

The winter solstice (December 21) is selected for this simulation to assess the impact of natural ventilation. Figure 93 shows neutral air movement on the north and south facades. On the other hand, the external wind flow hits the model with high velocity causing positive pressure on its western façade, and negative pressure on the eastern one. The blue stands for negative values whereas red stands for positive values.

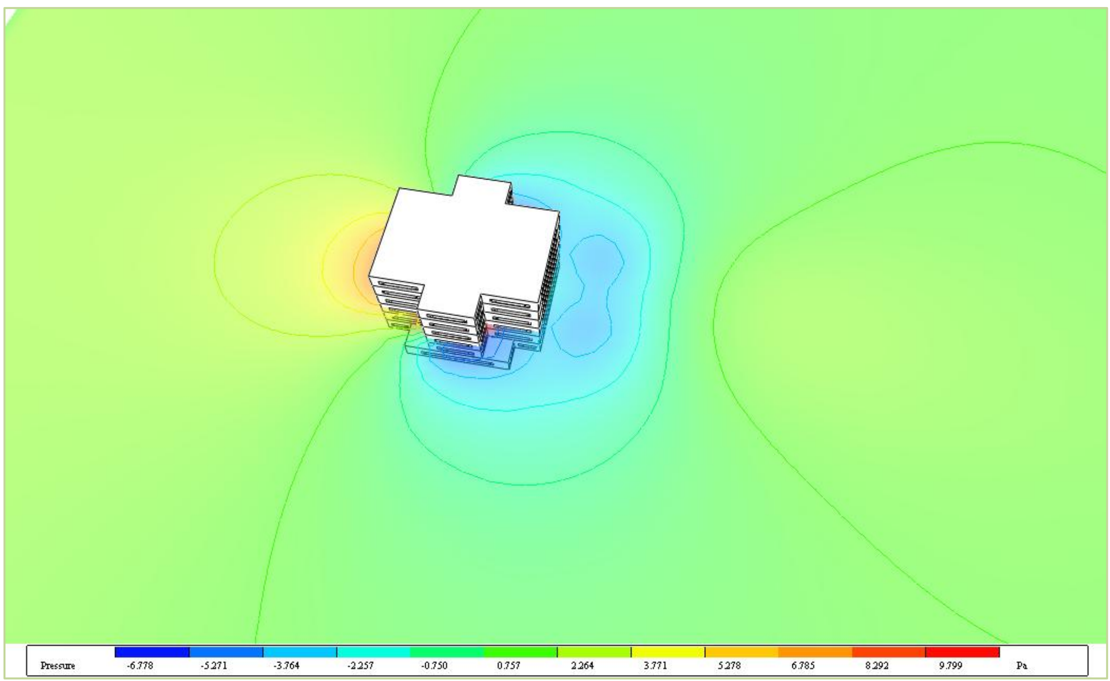


Figure 93. Pressure contours show negative pressure on the eastern façade (IES)

Figures 94 and 95 indicate positive air pressures on the windward side of the model which in the range of 3-8 Pa. It decreases to reach -5 Pa on the leeward side. Moreover, air pressure is increased as it moves away from the model and mixes with the external surrounding air. These readings will be compared to the same in the courtyard model.

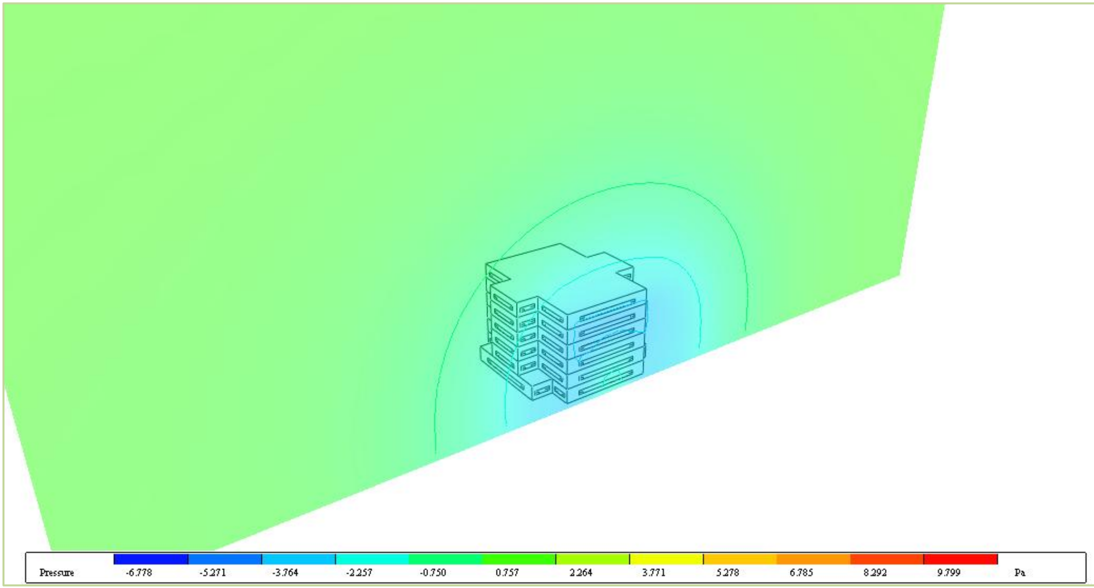


Figure 94. Negative pressure on leeward façade (IES)

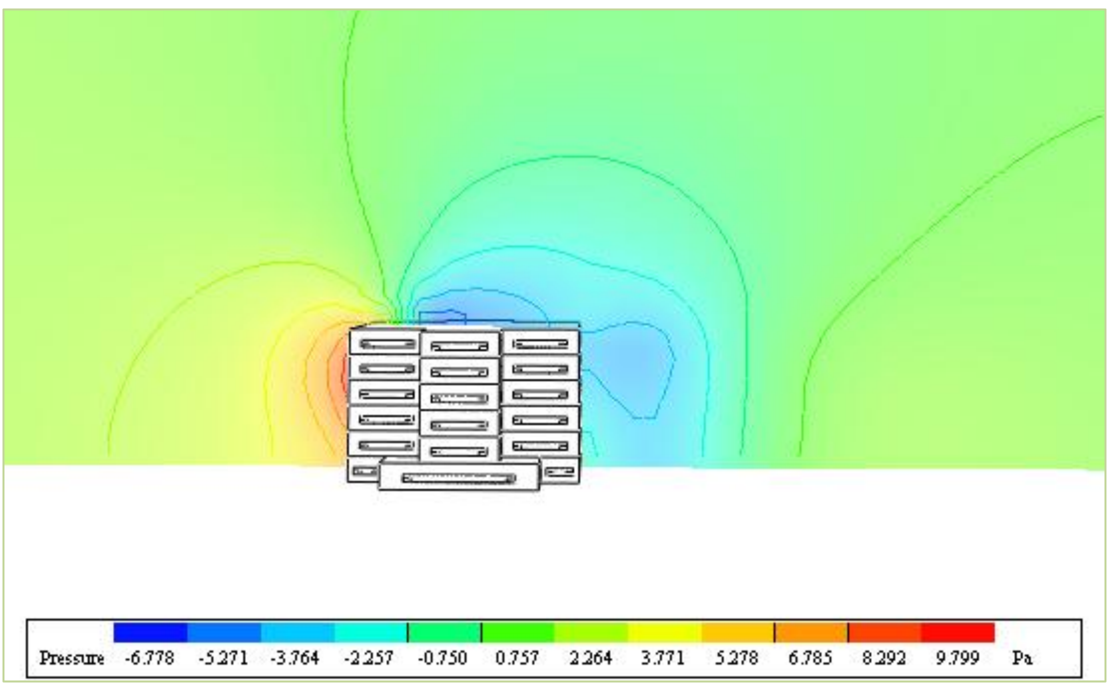


Figure 95. Air pressure variation around the model (IES)

The CFD analysis for the courtyard model shows a different response to the wind coming from the west, as the pressure around the model is considerably less different, as shown in Fig. 96 below.

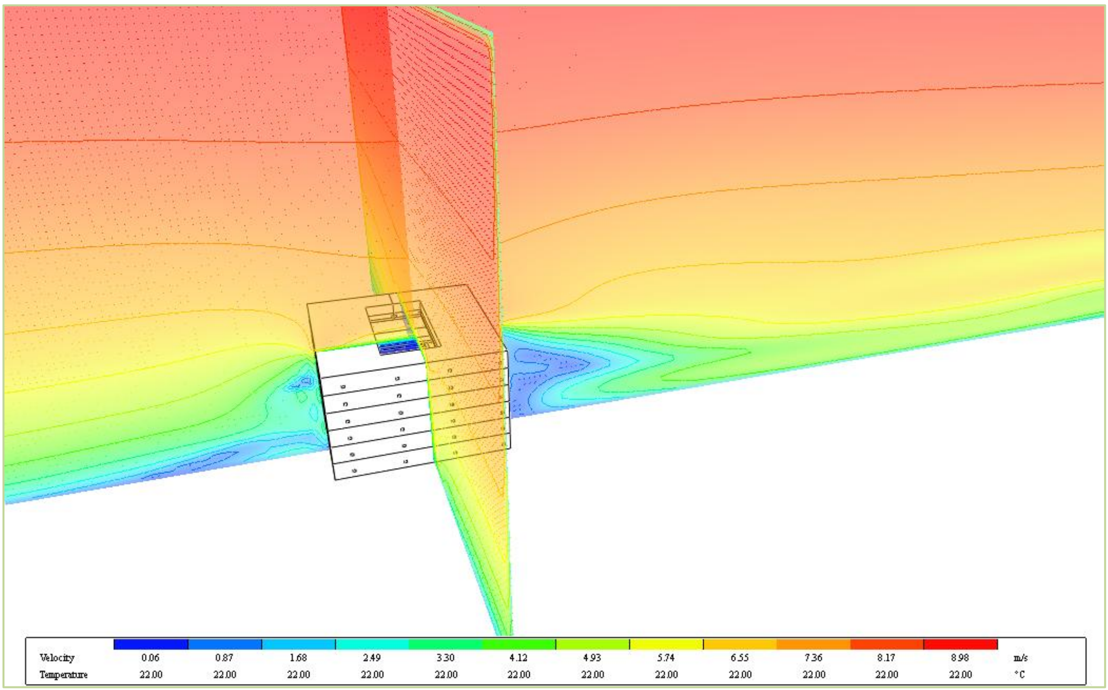


Figure 96. CFD Analysis of the courtyard model, Dec. 21 (IES)

Figure 97 shows the airflow patterns around the courtyard model. A difference in the air pressure is noticed between the north/south facades and the inner courtyard where the air is at high-pressure values (above 4 Pa). Therefore, movement in airflow patterns is interpreted to occur across the building as being driven by wind pressure differential.

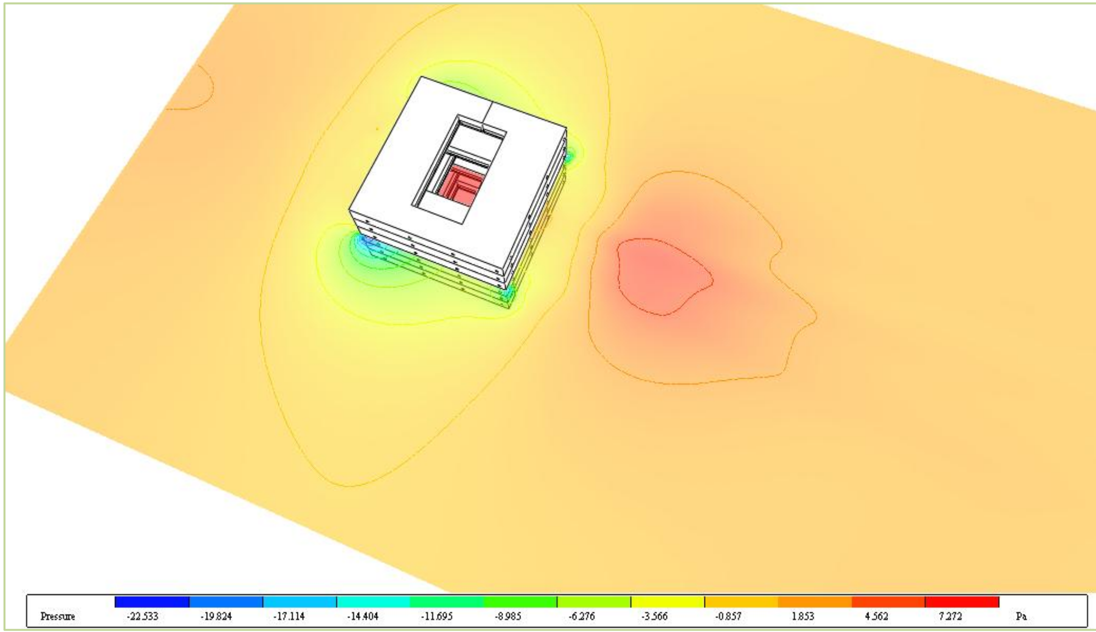


Figure 97. Pressure contours show negative pressure on the eastern façade (IES)

Figures 98 and 99 show negative air pressure on the east/west facades while high positive pressure air occurs into the courtyard. As the cross ventilation is a result of high differential in air pressure around two sides of the building, it is interpreted to have a significant improvement in terms of air velocity in double-sided spaces, even if the exterior air temperature is higher than the comfort zone limits.

More images of the CFD analyses performed on the conventional and courtyard models are attached in Appendices D and E.

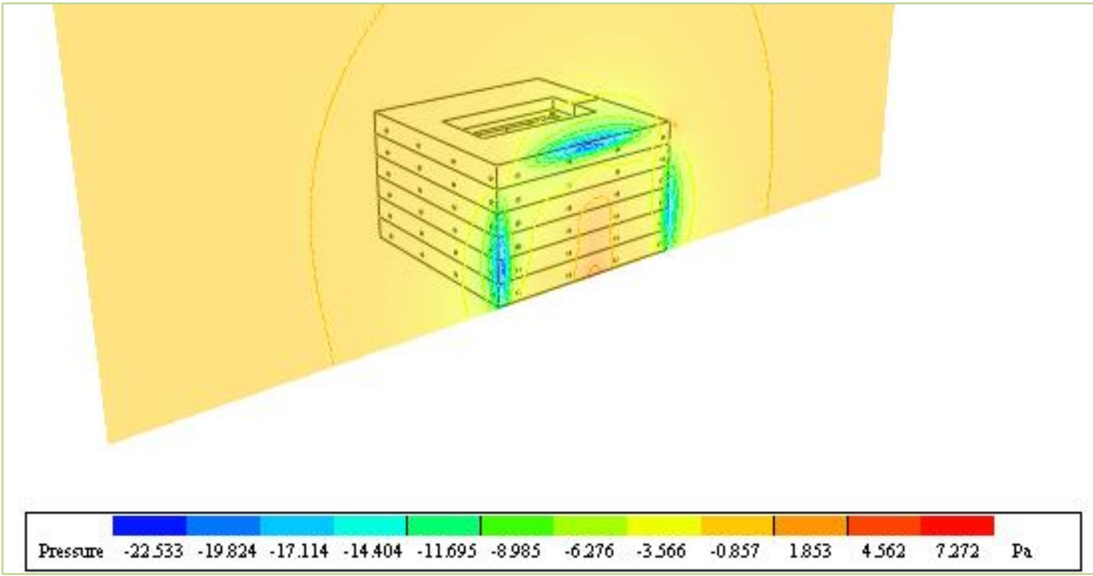


Figure 98. Negative pressure on leeward façade (IES)

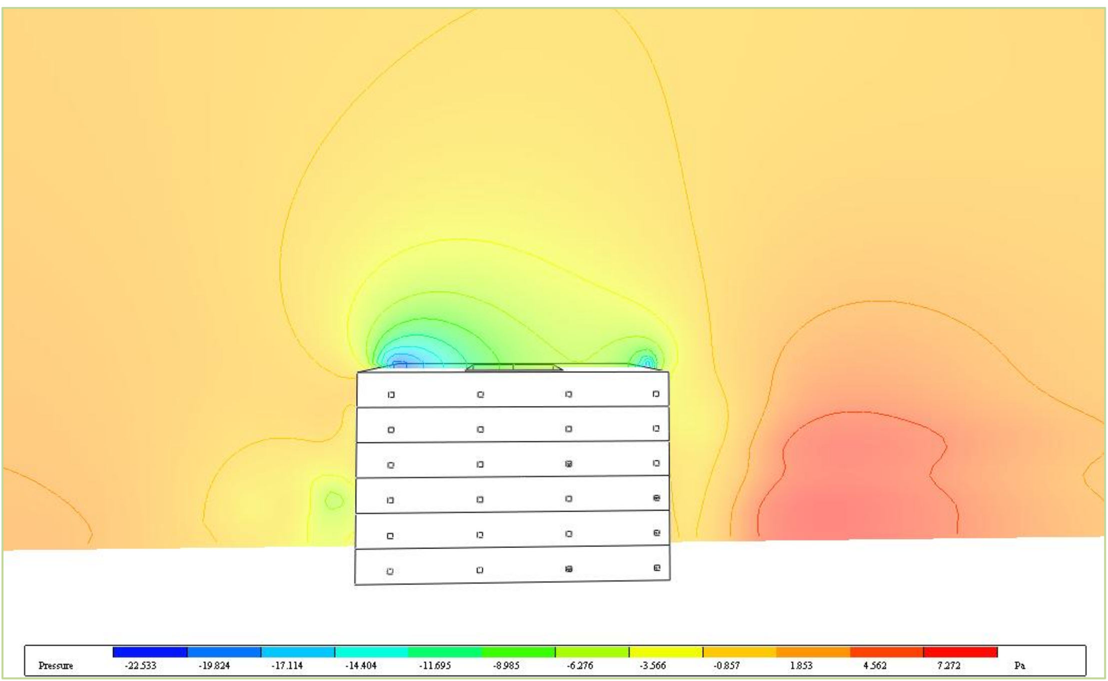


Figure 99. Air pressure variation around the model (IES)

5.2. Step 2: Variables within Courtyard Form

1. Height/Number of Storeys

In order to evaluate the height effect of the courtyard form on the energy reduction, the annual energy consumption is compared in four different heights: four, six, eight and ten storeys, as shown in Fig. 100. All other variables are fixed when running these simulations as per the reference model parameters.

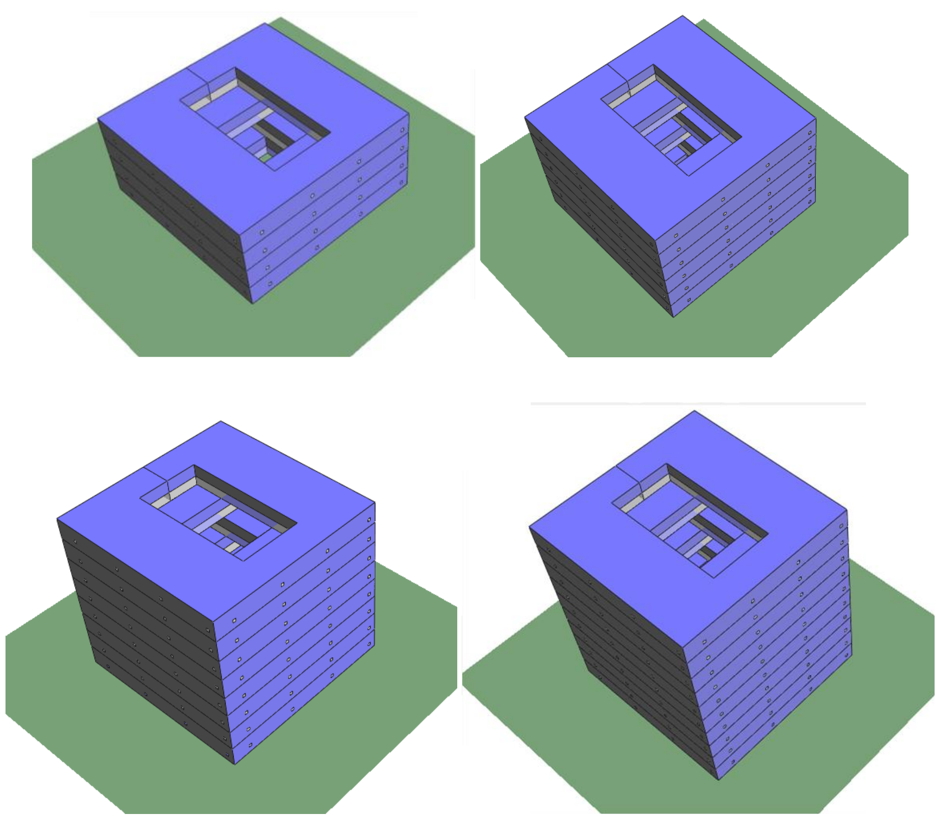


Figure 100. The selected heights of courtyard model (IES)

Table 18 below summarizes the properties of each height as per IES calculations, in addition to their relative total energy and energy consumption per square meter, it also shows the reduction percentages with relation to the reference model (six-level model) for each variable. It is noted that the volume, floor area, external wall area and external opening area all increase accordingly with relevance to height.

Table 18. Properties of selected heights and their energy calculations

Height/Number of Storeys	Volume (m^3)	Floor area (m^2)	External Wall (m^2)	External Opening (m^2)	Total Energy (MWh)	Energy per m^2 (MWh/m^2)	Energy Reduction/ Increase
4	10150	2900	2450	346	300.31	0.1035	+2.60%
6	15050	4300	3710	504	433.67	0.1008	-
8	19950	5700	4970	722	575.40	0.1009	+0.09%
10	24850	7100	6230	910	713.33	0.1004	-0.39%

As a result, the energy consumption increases, as per Fig. 101. In this figure, the monthly energy consumption is plotted against each height. This also shows that higher energy consumption is correlated linearly with the model height.

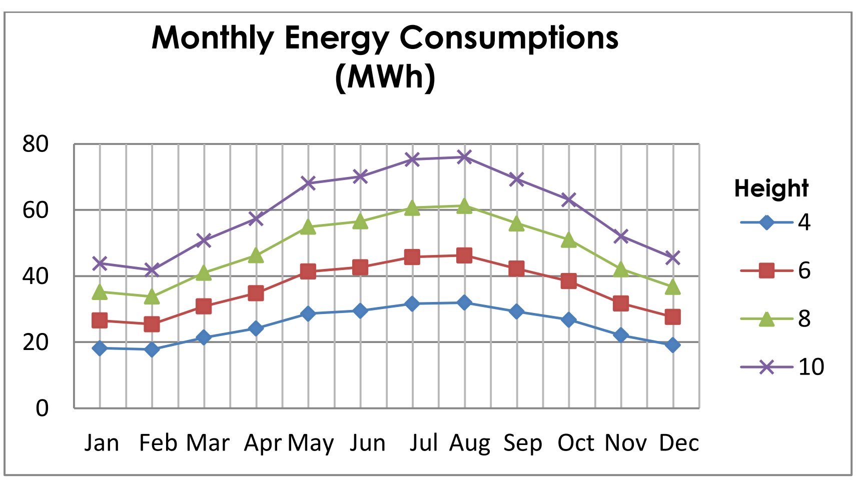


Figure 101. Monthly energy consumption of the selected height in the courtyard model

In order to evaluate this variable, the total energy consumption is divided by the floor area to normalize the values. The findings are represented in Fig. 102.

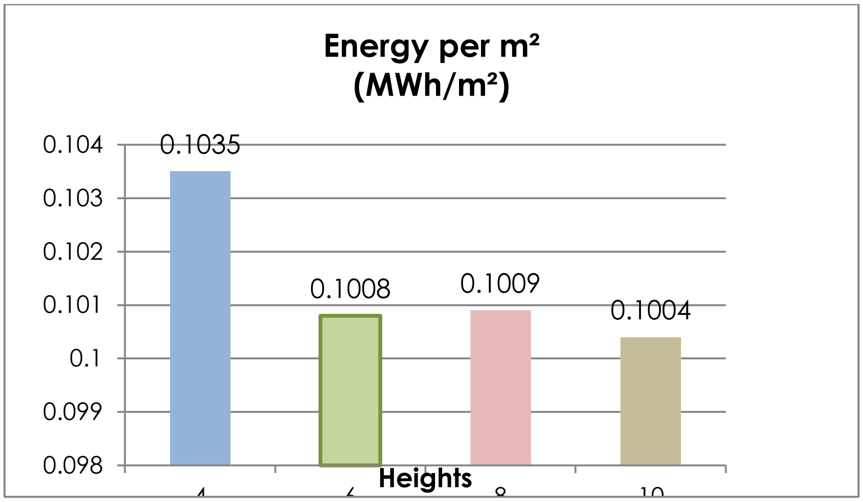


Figure 102. Normalized energy consumption in the selected heights of the courtyard model

The graph above shows that the energy consumption per square meter drops from the four-level model to the six-level model by 2.60%. On the contrary, the energy consumption per square meter increases slightly by 0.09% from the six-level to the eight-level model, yet it drops again by 0.40% from the eight-level to ten-level model. However, the increase from the six-level to the eight-level model can be ignored. This concludes that the ten-level model is the best energy saver among the other tested variables. On the other hand, the four-level model shows an irregular increase in energy use, as the form tends to be shallower which allows more solar heat gain into the model, as concluded by Muhaisen (2005). In general, the taller the model is the lower the specific total energy consumption. This could be explained by the fact that as the number of floors increases, the area of the roof remains the same. The exposed roof has the highest levels of solar gain and conduction heat transfer due to its large exposed surfaces. Reducing roof's relative exposed area in comparison to the model's overall exposed area would result in a reduction on the normalized total energy consumption of the model. This is particularly significant at low heights where the roof's relative area is significant. This effect becomes less significant for high models as the roof's relative area is already small and thus further reductions by means of increase height would not have a significant effect. Another explanation is that this also could be due to the weak stack effect in the shallower models, which leads to higher temperature and higher energy loads.

2. Glazing Type

The courtyard model is tested in different glazing types for openings in order to assess the reduction in annual energy consumption. The selected types are single, double (low-e) and triple (low-e) glazing. The double-glazing consists of an outer glass layer, an intermediate space and an inner glass layer. Similarly, the triple glazing has one more set of the intermediate space and inner glass layer. The outer layer provides weather protection and isolation. The intermediate space buffers thermal impact on the interior.

Table 19 below summarizes the results of ApacheSim calculations of variables in the courtyard model. The single glazing type has the highest energy consumption compared to the double glazing type (reference model).

Table 19. Glazing types effects on energy consumption in the courtyard model

Glazing Type	Total Energy (MWh)	Energy Reduction/Increase
Single Glazed	487.05	+12.30%
Double Glazed (Low-e)	433.67	-
Triple Glazed (Low-e)	423.61	-2.30%

Figure 103 shows a comparison of the three types in the total energy consumption. The single glazing type is 12.30% higher in energy consumption than the reference model, while the triple glazing types shows a mere improvement of 2.3% on energy reduction.

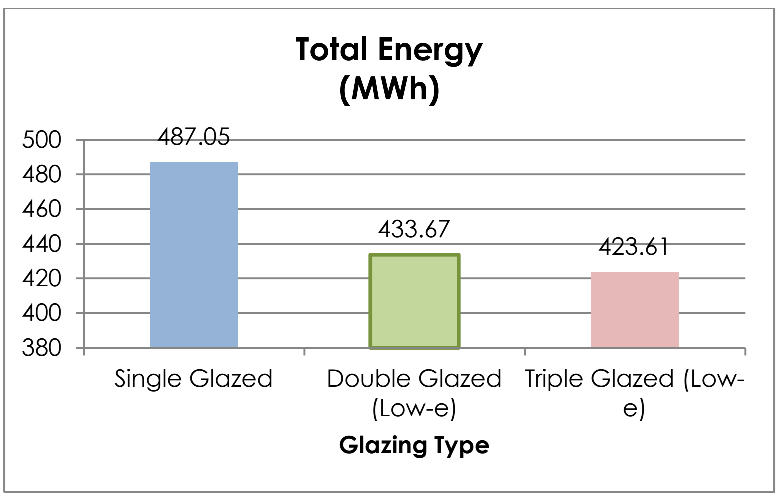


Figure 103. Total energy consumption of the selected glazing types in the courtyard model

The inconsistent drop is due to the different conduction values (heat transfer coefficient) throughout the layers, which depend primarily on temperature differentials between the two sides of each layer. It is identified that the temperature difference between outside and inside is high compared to the difference between the two intermediate spaces.

Consequently, energy consumption drops dramatically in the double-glazed model compared to the single glazed one, whereas the drop is smaller between the double and triple glazed model. This reduction can be evaluated against the cost when shifting from the double to triple glazing type, as the added cost might not have equal effectiveness or return on the energy reduction.

Figure 104 shows the monthly energy consumption of the selected glazing types. The glazing types in the courtyard model vary largely in energy saving mostly during March through November, whereas the variation diminishes dramatically when in January, February and December. This is primarily due to the high temperature difference between inside and outside during hot seasons.

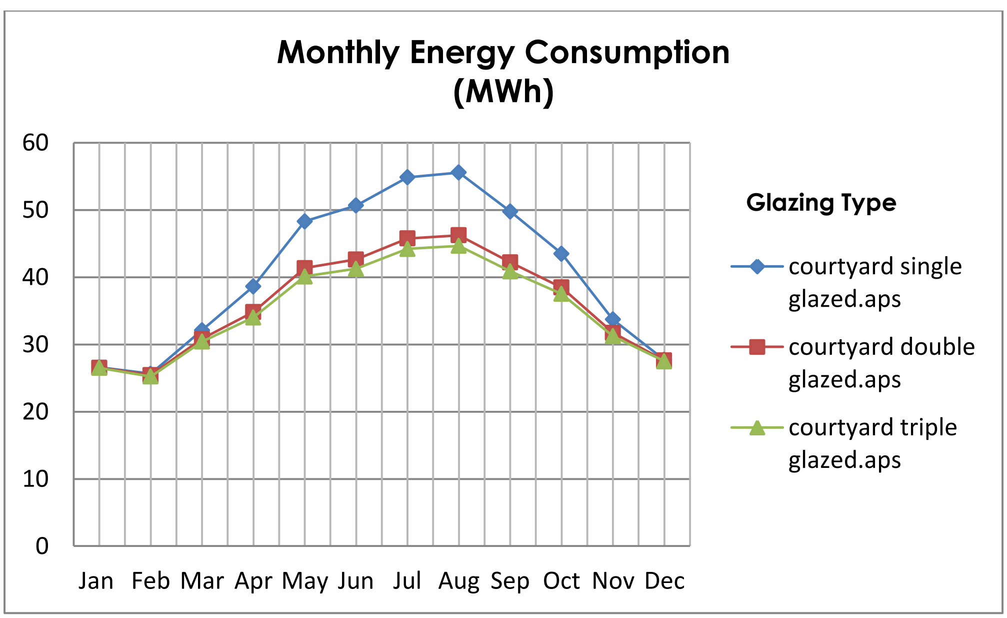


Figure 104. Monthly energy consumption of the selected glazing types in the courtyard model

3. *Wall Thickness*

The courtyard model is tested in five different wall thicknesses to assess their return on energy saving. Table 20 indicates the total energy consumption and reduction with regard to the reference model (25 cm wall thickness).

Table 20. Total energy consumption and reductions in the selected wall thicknesses

Wall Thickness (cm)	Total Energy (MWh)	Energy Reduction/ Increase
15	436.29	+0.60%
20	434.68	+0.23%
25	433.67	-
30	432.27	-0.32%
40	429.82	-0.88%

Figure 105 below shows that the thick wall contributes towards the energy saving in the model with a consistent percentage. It is noted also that the reduction as the thickness increases might not be substantial. Thus, special consideration is needed when trading off the energy saving with the possible added cost.

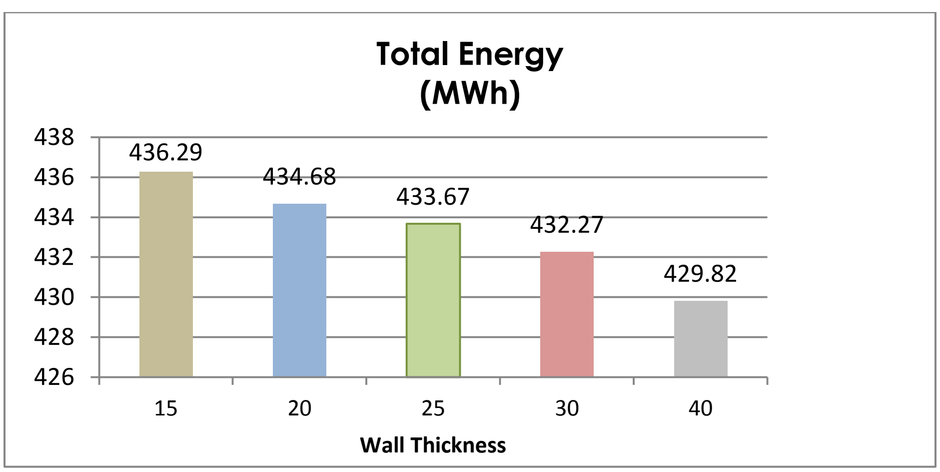


Figure 105. Total energy consumption in the selected wall thicknesses in courtyard model

A breakdown of the monthly energy consumption of the four different wall thicknesses is shown in Fig. 106. Although the 40 cm-thick wall shows 0.88% reduction compared to the reference model, variations in wall thickness have an insignificant impact on the overall energy saving in the courtyard model. This is different to the traditional theory that increased wall thickness enhances significantly the thermal insulation. In other words, the cost impact for implementing higher thickness would not improve the energy saving if weighted against the associated cost compared to other alternative strategies, unless very thick walls are implemented which is not practical in midrise buildings and not applicable to this study.

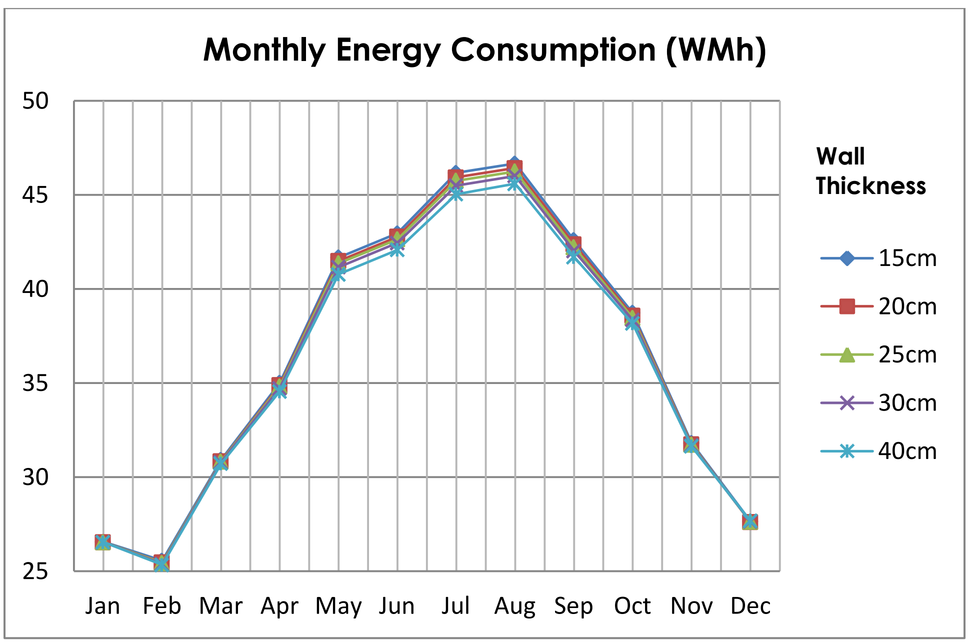


Figure 106. Monthly energy consumption of the selected wall thicknesses in the courtyard model

4. Insulation Material

Five selected insulation materials and their properties were represented in Table 9. The simulation results are represented in Table 21 below.

Table 21. Insulation materials effect on energy reduction in the courtyard model

Insulation Material	Total Energy (MWh)	Energy Reduction/ Increase
Dense EPS Insulation like Styrofoam	433.67	-
Glass-Fiber Quilt	448.86	+3.50%
Phenolic Foam	448.86	+3.50%
Cavity Insulation [ASHRAE]	474.67	+9.45%
Cellular Polyurethane	427.78	-1.35%

It is noted that the conductivity value of a material has a direct correlation with the energy use. The Glass-Fiber Quilt and Phenolic Foam share the same conductivity value but differ in density and heat capacity (Table 9). The simulation results show the same total energy for both materials, which gives the conductivity value high consideration on the insulation effect, whereas the impact of other properties (density and heat capacity) might be limited to the time lag of their thermal response.

Figure 107 below shows the energy consumption values with regard to the selected insulation materials. It shows that Cellular Polyurethane has the highest value of energy saving (-1.35%), whereas the Cavity Insulation [ASHRAE] shows a large increase in energy use (+9.45%) compared to the reference model.

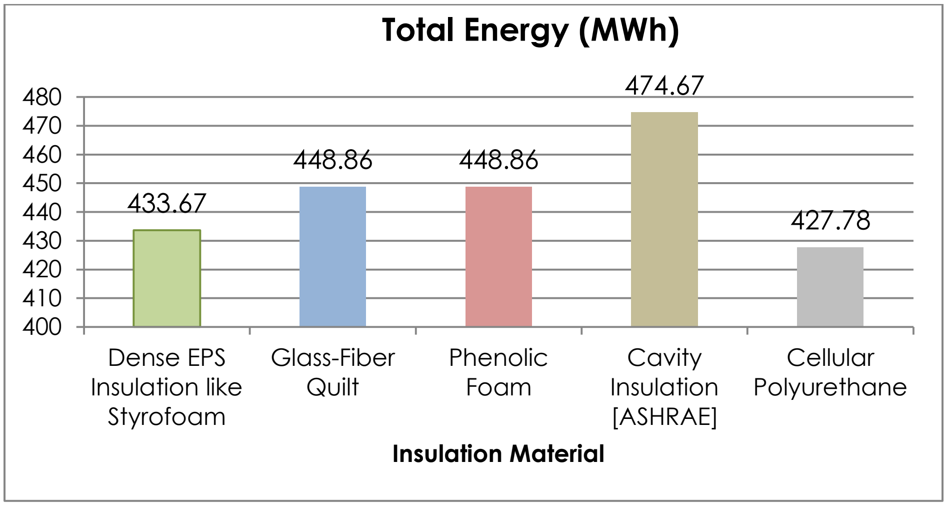


Figure 107. Total energy consumption of the selected insulation materials of courtyard model

Figure 108 shows the monthly energy consumption of the selected insulation materials. The insulation materials in the courtyard model vary largely in energy saving mostly during March through November, whereas the variation reduces in January, February and December. This is primarily due to the high temperature differential between inside and outside during hot seasons.

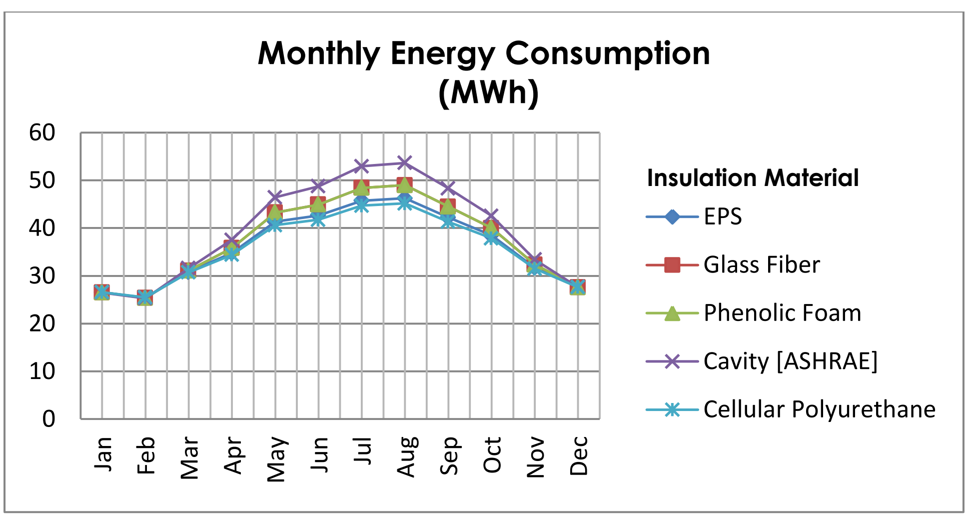


Figure 108. Monthly energy consumption of the selected insulation materials in the courtyard model

5. Insulation Thickness

The courtyard model is tested in four different insulation thicknesses to assess their return on energy saving. Table 22 shows the total energy consumption and reduction with regard to the reference model (5.0 cm insulation material thickness).

Table 22. Insulation thickness effect on energy reduction in the courtyard model

Insulation Thickness	Total Energy (MWh)	Energy Reduction/ Increase
2.5 cm	457.30	+5.44%
5.0 cm	433.67	-
7.5 cm	423.59	-2.32%
10 cm	418.03	-3.60%

Figure 109 below indicates the energy consumption values with regard to the selected insulation thicknesses. The 10 cm-thick insulation has the highest return on energy saving (3.60%) with reference to the base model, whereas the 2.5 cm-thick wall increases the energy use by 5.44% with reference to the base model. Moreover, the increase of energy use in the 2.5 cm-wall thickness is noticeably higher than the rest of the variables set, whereas thicknesses of 5, 7.5 and 10 cm reduce the energy use by a slightly more consistent differences.

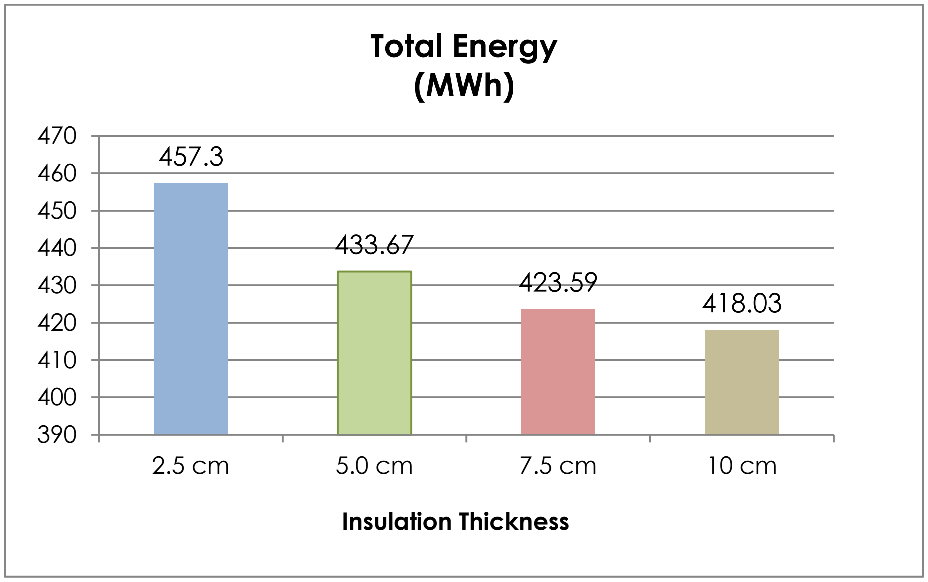


Figure 109. Total energy consumption of the selected insulation thicknesses of courtyard model

Figure 110 indicates the monthly energy consumption of the selected insulation thicknesses. The differences in energy behavior lessen noticeably in cold seasons, which is primarily due to the lower temperature differential between inside and outside.

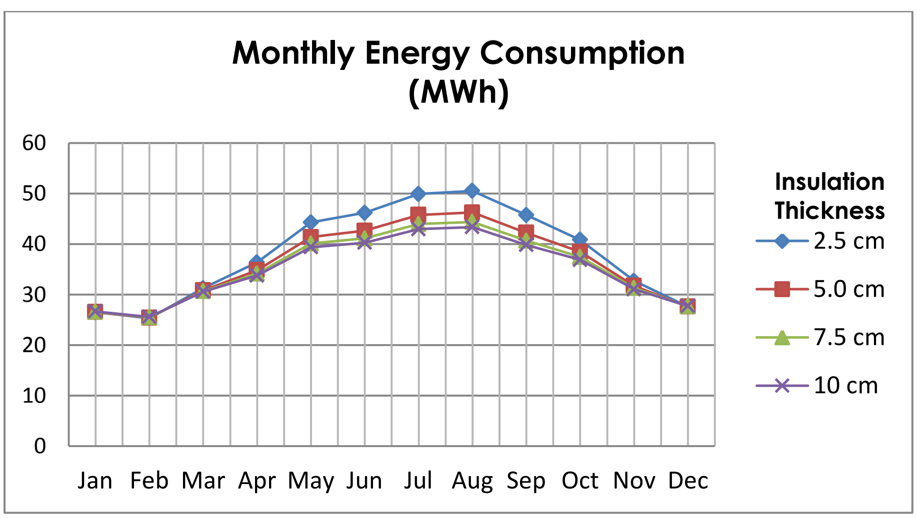


Figure 110. Monthly energy consumption of the selected insulation thicknesses in the courtyard model

Detailed results of the monthly energy consumption for the selected variables are attached in Appendices F, G, H, I and J.

5.3. Step 3: Optimal Courtyard versus Conventional Form

Based on the previous simulations results, an optimal six-level courtyard model (B) is tested against the six-level conventional model (reference model in this case) in terms of energy saving. The optimal parameters are Triple Low-e Glazed openings, 40 cm wall thickness and Cellular Polyurethane with 10 cm thickness. Table 23 summarizes the simulation results.

Table 23. Comparison of Conventional, Courtyard A and Courtyard B in total energy

	Total Energy (MWh)	Energy Reduction/ Increase
Conventional	465.84	-
Courtyard A	433.67	-6.90%
Courtyard B	413.87	-11.16%

It is noted that the optimum courtyard form (B) has a higher energy saving compared to the previously proposed courtyard form (A). This saving reaches 11.16% compared to 6.90% in the courtyard form (A), Fig. 111.

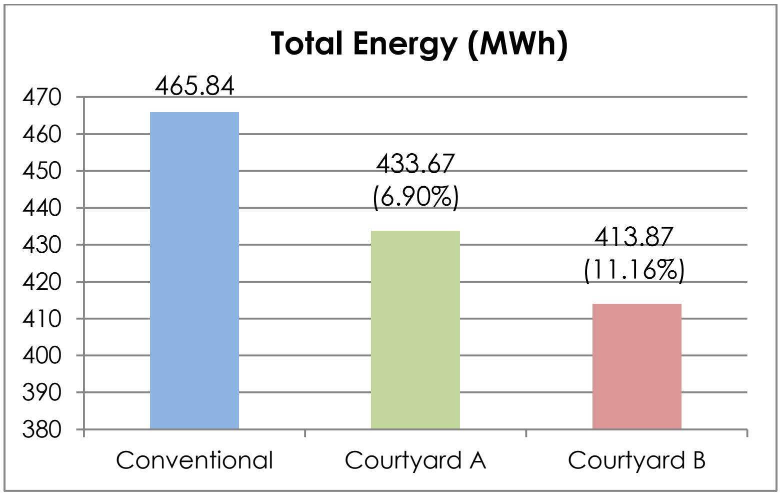


Figure 111. Comparison of conventional, courtyard A and courtyard B in total energy

Figure 112 below indicates the monthly energy performance of the three forms. By reading the monthly values, it is observed that the two courtyard models act similarly from November to March, where as the optimum courtyard model (B) performs significantly better in the hot months for the rest of the year. Moreover, the energy consumption in the courtyard model (B) is higher than the conventional on regular monthly discrepancies. This means that the courtyard model (B) is more effective than the conventional throughout the year, unlike the courtyard model (A) which drops in cooling efficiency during hot months of the year. Based on that, the weak energy performance of the courtyard model (A) during summer can be overcome by altering the model towards optimal values of variables such as thicker walls, improved insulation and glazing.

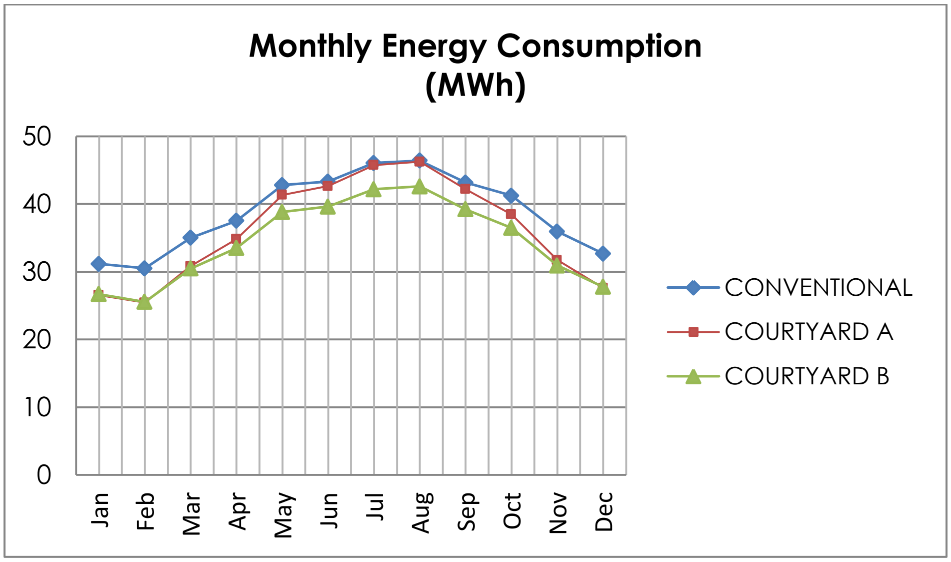


Figure 112. Monthly energy consumptions of conventional, courtyard A and courtyard B

The results of the monthly energy simulations of the conventional, courtyard (A) and courtyard (B) models are attached in Appendix K.

Chapter 6: Conclusions & Recommendations

6.1. Conclusions

In this study, an environmental assessment of the courtyard integration in midrise housing has been conducted in the context of hot-arid climate. The study included a literature review of previous research papers that had been done in similar area. These studies dealt extensively with the low-rise courtyard housing; however, they fell short of addressing the courtyard in midrise housing. A study by Hakmi (2006) presented some proposals of the courtyard in midrise housing yet was primarily theoretical and lacked methodological testing and validation in the given climate. A computer simulation developed by Integrated Environmental Solutions-Virtual Environment 6.0 (IES) was used for this study. Consequently, all findings were based on the simulation results.

The study outlined three distinctive steps: Firstly, a six-level courtyard model was compared to the same of conventional model. Secondly, variables within the courtyard model were assessed to determine the optimum parameters. Thirdly, a six-level courtyard model with a combination of the optimum variables was compared again to the previous six-level of conventional model.

In the first step, several criteria were evaluated and compared qualitatively and quantitatively between the two models, which are solar gain, conduction gain and total energy consumption. The study concluded that the energy reduction through the courtyard integration in midrise housing is 6.90% compared to the conventional housing. In spite of that, the monthly scenario of energy reduction showed the highest reduction during the moderate/cold months. Therefore, the recommendation of courtyard integration in midrise housing can be extended to include moderate climates. In details, the courtyard integration in midrise housing showed significant improvement on the solar gain reduction, although the conduction gain was considerably higher than the conventional model due to the larger area of exposed surfaces. As for the solar shading results, solar heat gain in the courtyard model was reduced due to the presence of larger openings on the shaded walls around the courtyard space which resulted in lower cooling loads during summer. The daylight analysis indicated that the courtyard model is advantageous in winter and summer as it reduces the sun glare. On the other hand, the conventional model exceeded daylight factor in winter and summer. Therefore, shading methods are required in the conventional model to control the daylight into the interiors. The CFD airflow analyses showed higher air pressure differential between the courtyard and the external envelope, which led to an enhancement in the mass airflow, due to the cross ventilation effects.

In the second step, in the selection of the optimum parameters in the courtyard model, different variables were tested with relation to energy saving which are height, glazing type, wall thickness, insulation material and insulation thickness. The height had a vital impact on the energy performance as the simulation further showed a considerable reduction correlated with the height increase. The best energy saving was revealed in the ten-level model compared to lower level models (0.39% reduction), whereas the four-level model performed worst (2.60% increase). In terms of glazing types, the single glazing showed a large increase (12.30%) in energy use compared to the double-glazing, especially during hot seasons, while triple glazing had a small impact on the energy reduction (2.30%) compared to double glazing especially if weighted against the added cost. It is also observed that increasing the wall thickness has not significantly improved energy saving, as the 40 cm-thick wall provided only a 0.88% reduction. Hence, alternative strategies can be more beneficial such as applying the right insulation materials into external walls. In terms of insulation materials, the simulations showed that Cellular Polyurethane had highest impact on energy saving (1.35% reduction) due to its low conductivity value with reference to EPS Insulation, where Cavity Insulation [ASHRAE] had the highest energy use due to its high conductivity value (9.45% increase). Moreover, the 10 cm-thick insulation had the highest return on energy saving (3.60% reduction), whereas the 2.5 cm-thick insulation increased energy use by 5.44% with reference to the base model. However, the return of insulation thickness on energy saving should be weighed against the practicality of implementation.

In the third step, the simulation results showed 11.16% reduction in energy use, as well as more consistent difference in the monthly behavior. Additionally, a better summer performance was noticed compared to the previous prototype of courtyard model. Therefore, optimum parameters integrated in the courtyard model affect greatly the energy saving especially during summer. Nevertheless, applicability and economic factors of the optimal parameters need to be evaluated and taken into consideration.

6.2. Recommendations for Further Studies

The courtyard model shows a significant role in the climate control and energy use reduction in hot-arid regions. In order to overcome the proposed models limitations, different heights and configurations can be further assessed to measure their energy use reduction. Moreover, it is recommended to evaluate courtyard integration in midrise housing across different climates, as the energy reduction was higher during moderate/cold months. Therefore, the benefits for courtyard integration in midrise housing can also be extended to include moderate climates.

However, there are many challenges that need to be addressed in the previously proposed courtyard model. Some of these challenges include lack of privacy and variation.

Two different proposals (attached in Appendices L and M) have been designed to overcome these disadvantages. However, energy performance assessment is needed to evaluate the advantages against the energy reduction they might produce.

Lastly, there are "… almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives. Obviously, there is no single solution, i.e. no universally optimum geometry" (Oke 1988 cited in Raydan et al 2007). Nevertheless, a sustainable housing is simply a reflection of balanced interactions between economy, society and environment.

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Appendices

Appendix A: Monthly Thermal Calculations (ApacheSim) Winter and Summer- Conventional Model

	Solar gain (MWh)
Date	ROOM conventional- winter.aps
Dec 21-31	5.8305
Jan 01-31	17.6335
Feb 01-28	17.7273
Mar 01-31	17.9026
Apr 01-30	17.3047
May 01-31	18.0505
Jun 01-21	12.0773
Summed total	106.5264

	Solar gain (MWh)
Date	ROOM conventional- summer.aps
Jun 21-30	5.7048
Jul 01-31	17.5194
Aug 01-31	17.3823
Sep 01-30	17.1532
Oct 01-31	18.622
Nov 01-30	17.7283
Dec 01-21	11.7104
Summed total	105.8204

	Cooling plant sensible load (MWh)
Date	ROOM conventional-winter.aps
Dec 21-31	4.5244
Jan 01-31	9.3341
Feb 01-28	13.0949
Mar 01-31	17.0174
Apr 01-30	23.7447
May 01-31	32.5835
Jun 01-21	24.7601
Summed total	125.0592

	Cooling plant sensible load (MWh)
Date	ROOM conventional-summer.aps
Jun 21-30	11.643
Jul 01-31	39.0569
Aug 01-31	39.8182
Sep 01-30	35.0447
Oct 01-31	29.459
Nov 01-30	20.5656
Dec 01-21	8.0767
Summed total	183.664

	External conduction gain (MWh)
Date	ROOM conventional-winter.aps
Dec 21-31	-1.2639
Jan 01-31	-7.7706
Feb 01-28	-4.3098
Mar 01-31	-0.8651
Apr 01-30	5.9803
May 01-31	13.4619
Jun 01-21	11.7308
Summed total	16.9636

	External conduction gain (MWh)
Date	ROOM conventional-summer.aps
Jun 21-30	5.5003
Jul 01-31	19.9656
Aug 01-31	20.7837
Sep 01-30	16.6845
Oct 01-31	10.1534
Nov 01-30	2.6423
Dec 01-21	-3.4496
Summed total	72.2802

	MacroFlo ext vent gain (MWh)
Date	ROOM conventional-winter.aps
Dec 21-31	-0.0715
Jan 01-31	-0.5205
Feb 01-28	-0.2719
Mar 01-31	-0.0395
Apr 01-30	0.4738
May 01-31	1.1059
Jun 01-21	0.9547
Summed total	1.631

	MacroFlo ext vent gain (MWh)
Date	ROOM conventional-summer.aps
Jun 21-30	0.4317
Jul 01-31	1.5829
Aug 01-31	1.6479
Sep 01-30	1.1949
Oct 01-31	0.6672
Nov 01-30	0.1778
Dec 01-21	-0.2203
Summed total	5.4821

	Total energy (MWh)
	conventional-winter.aps
Date	
Dec 21-31	11.6696
Jan 01-31	31.1789
Feb 01-28	30.4936
Mar 01-31	35.0205
Apr 01-30	37.5289
May 01-31	42.8035
Jun 01-21	30.3396
Summed total	219.0347

	Total energy (MWh)
	conventional-summer.aps
Date	
Jun 21-30	14.3737
Jul 01-31	46.0402
Aug 01-31	46.4208
Sep 01-30	43.1789
Oct 01-31	41.2413
Nov 01-30	35.9394
Dec 01-21	21.998
Summed total	249.1922

	Total CE (kgCO2) conventional-winter.aps
Date	
Dec 21-31	4925
Jan 01-31	13157
Feb 01-28	12868
Mar 01-31	14779
Apr 01-30	15837
May 01-31	18063
Jun 01-21	12803
Summed total	92432

	Total CE (kgCO2) conventional-summer.aps
Date	
Jun 21-30	6066
Jul 01-31	19429
Aug 01-31	19590
Sep 01-30	18222
Oct 01-31	17404
Nov 01-30	15166
Dec 01-21	9283
Summed total	105159

Appendix B: Monthly Thermal Calculations (ApacheSim) Winter and Summer- Courtyard Model

	Solar gain (MWh)
Date	ROOM Courtyard-Winter.aps
Dec 21-31	2.1313
Jan 01-31	6.5911
Feb 01-28	7.3456
Mar 01-31	8.1236
Apr 01-30	8.4105
May 01-31	9.3435
Jun 01-21	6.3685
Summed total	48.314

	Solar gain (MWh)
Date	ROOM Courtyard-summer.aps
Jun 21-30	3.0113
Jul 01-31	9.1249
Aug 01-31	8.9362
Sep 01-30	8.5091
Oct 01-31	8.1696
Nov 01-30	6.8714
Dec 01-21	4.2515
Summed total	48.8741

	Cooling plant sensible load (MWh)
Date	ROOM Courtyard-Winter.aps
Dec 21-31	1.1713
Jan 01-31	0.0718
Feb 01-28	2.9772
Mar 01-31	8.6417
Apr 01-30	18.3265
May 01-31	29.703
Jun 01-21	23.8404
Summed total	84.732

	Cooling plant sensible load (MWh)
Date	ROOM Courtyard-summer.aps
Jun 21-30	11.1412
Jul 01-31	38.4443
Aug 01-31	39.4711
Sep 01-30	33.1149
Oct 01-31	23.917
Nov 01-30	12.1396
Dec 01-21	1.0549
Summed total	159.2831

	External conduction gain (MWh)
Date	ROOM Courtyard-Winter.aps
Dec 21-31	-0.9924
Jan 01-31	-6.22
Feb 01-28	-3.7253
Mar 01-31	0.5403
Apr 01-30	9.3222
May 01-31	18.9743
Jun 01-21	16.2548
Summed total	34.154

	External conduction gain (MWh)
Date	ROOM Courtyard-summer.aps
Jun 21-30	7.5744
Jul 01-31	27.3323
Aug 01-31	28.4412
Sep 01-30	23.073
Oct 01-31	14.8688
Nov 01-30	5.0128
Dec 01-21	-2.9761
Summed total	103.3266

	MacroFlo ext vent gain (MWh)
Date	ROOM Courtyard-Winter.aps
Dec 21-31	-0.0831
Jan 01-31	-0.4918
Feb 01-28	-0.2959
Mar 01-31	-0.0329
Apr 01-30	0.6118
May 01-31	1.4239
Jun 01-21	1.2199
Summed total	2.352

	MacroFlo ext vent gain (MWh)
Date	ROOM Courtyard-summer.aps
Jun 21-30	0.5487
Jul 01-31	2.0021
Aug 01-31	2.0878
Sep 01-30	1.5197
Oct 01-31	0.8561
Nov 01-30	0.2325
Dec 01-21	-0.2448
Summed total	7.002

	Total energy (MWh)
	courtyard-Winter.aps
Date	
Dec 21-31	11.612
Jan 01-31	69.3809
Feb 01-28	53.5309
Mar 01-31	54.5199
Apr 01-30	83.6545
May 01-31	150.1284
Jun 01-21	123.2217
Summed total	546.0483

	Total energy (MWh)
	courtyard-summer.aps
Date	
Dec 21-31	9.9931
Jan 01-31	26.5478
Feb 01-28	25.4347
Mar 01-31	30.8327
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-21	29.8798
Summed total	198.8711

	Total CE (kgCO2)
	courtyard-Wniter.aps
Date	
Dec 21-31	4715
Jan 01-31	19731
Feb 01-28	17559
Mar 01-31	21250
Apr 01-30	35302
May 01-31	63354
Jun 01-21	52000
Summed total	213911

	Total CE (kgCO2)
	courtyard-summer.aps
Date	
Dec 21-31	4217
Jan 01-31	11203
Feb 01-28	10733
Mar 01-31	13011
Apr 01-30	14694
May 01-31	17455
Jun 01-21	12609
Summed total	83923

Appendix C: Monthly Thermal Calculations (ApacheSim) One Simulation Run- Threshold Degree Method- Conventional and Courtyard Models

Solar gain (MWh)	
Date	**CONVENTIONAL FORM**
Jan 01-31	17.6335
Feb 01-28	17.7273
Mar 01-31	17.9026
Apr 01-30	17.3047
May 01-31	18.0505
Jun 01-30	17.2014
Jul 01-31	17.5194
Aug 01-31	17.3823
Sep 01-30	17.1532
Oct 01-31	18.622
Nov 01-30	17.7283
Dec 01-31	17.1856
Summed total	211.4108

Solar gain (MWh)		
Date	**COURTYARD FORM**	
Jan 01-31	6.5911	
Feb 01-28	7.3456	
Mar 01-31	8.1236	
Apr 01-30	8.4105	
May 01-31	9.3435	
Jun 01-30	9.0732	
Jul 01-31	9.1249	
Aug 01-31	8.9362	
Sep 01-30	8.5091	
Oct 01-31	8.1696	
Nov 01-30	6.8714	
Dec 01-31	6.2351	
Summed total	96.7338	-54.24%

Cooling plant sensible load (MWh)	
Date	**CONVENTIONAL FORM**
Jan 01-31	9.3079
Feb 01-28	13.0947
Mar 01-31	17.0174
Apr 01-30	23.7447
May 01-31	32.5835
Jun 01-30	35.3097
Jul 01-31	39.0873
Aug 01-31	39.8184
Sep 01-30	35.0447
Oct 01-31	29.459
Nov 01-30	20.5656
Dec 01-31	12.3429
Summed total	307.3758

Cooling plant sensible load (MWh)		
Date	**COURTYARD FORM**	
Jan 01-31	0.0677	
Feb 01-28	2.9768	
Mar 01-31	8.6417	
Apr 01-30	18.3265	
May 01-31	29.703	
Jun 01-30	33.9788	
Jul 01-31	38.4897	
Aug 01-31	39.4715	
Sep 01-30	33.1149	
Oct 01-31	23.917	
Nov 01-30	12.1396	
Dec 01-31	2.2226	
Summed total	243.0499	-20.93%

External conduction gain (MWh)		
Date	**CONVENTIONAL FORM**	
Jan 01-31	-7.7962	
Feb 01-28	-4.31	
Mar 01-31	-0.8651	
Apr 01-30	5.9803	
May 01-31	13.4619	
Jun 01-30	16.7576	
Jul 01-31	19.9956	
Aug 01-31	20.7839	
Sep 01-30	16.6845	
Oct 01-31	10.1534	
Nov 01-30	2.6423	
Dec 01-31	-4.5895	
Summed total	88.8987	

External conduction gain (MWh)		
Date	**COURTYARD FORM**	
Jan 01-31	-6.2182	
Feb 01-28	-3.7255	
Mar 01-31	0.5403	
Apr 01-30	9.3222	
May 01-31	18.9743	
Jun 01-30	23.1819	
Jul 01-31	27.3771	
Aug 01-31	28.4416	
Sep 01-30	23.073	
Oct 01-31	14.8688	
Nov 01-30	5.0128	
Dec 01-31	-3.8222	
Summed total	137.0262	54.14%

MacroFlo ext vent gain (MWh)	
Date	**CONVENTIONAL FORM**
Jan 01-31	-0.5204
Feb 01-28	-0.2719
Mar 01-31	-0.0395
Apr 01-30	0.4738
May 01-31	1.1059
Jun 01-30	1.3448
Jul 01-31	1.5829
Aug 01-31	1.6479
Sep 01-30	1.1949
Oct 01-31	0.6672
Nov 01-30	0.1778
Dec 01-31	-0.2884
Summed total	7.0751

MacroFlo ext vent gain (MWh)		
Date	**COURTYARD FORM**	
Jan 01-31	-0.4883	
Feb 01-28	-0.2959	
Mar 01-31	-0.0329	
Apr 01-30	0.6118	
May 01-31	1.4239	
Jun 01-30	1.7162	
Jul 01-31	2.0021	
Aug 01-31	2.0878	
Sep 01-30	1.5197	
Oct 01-31	0.8561	
Nov 01-30	0.2325	
Dec 01-31	-0.3243	
Summed total	9.3087	31.57%

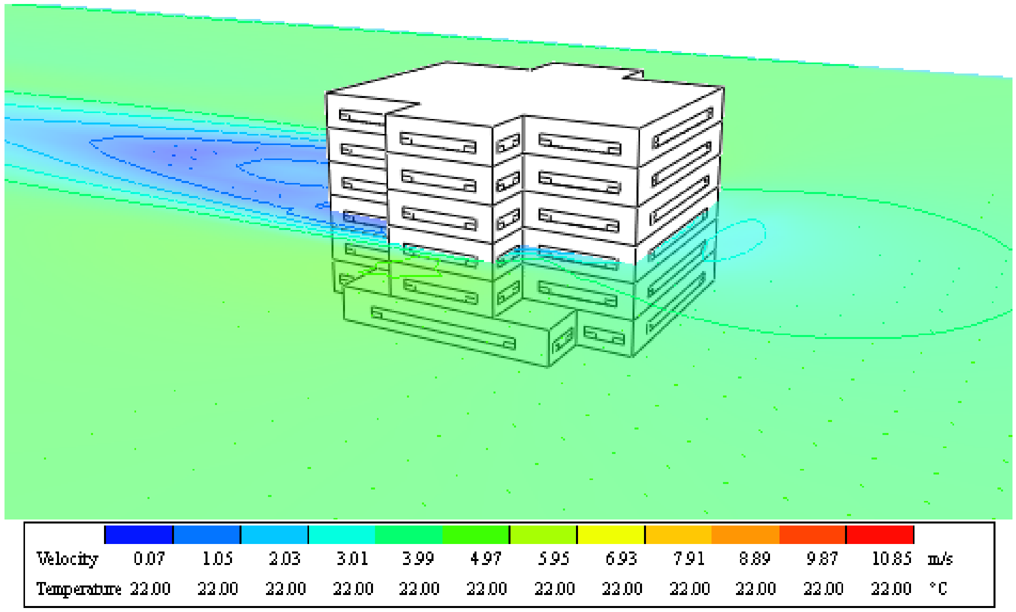
Total energy (MWh)	
CONVENTIONAL FORM	
Date	
Jan 01-31	31.1658
Feb 01-28	30.4935
Mar 01-31	35.0205
Apr 01-30	37.5289
May 01-31	42.8035
Jun 01-30	43.3114
Jul 01-31	46.0554
Aug 01-31	46.4209
Sep 01-30	43.1789
Oct 01-31	41.2413
Nov 01-30	35.9394
Dec 01-31	32.6833
Summed total	465.8427

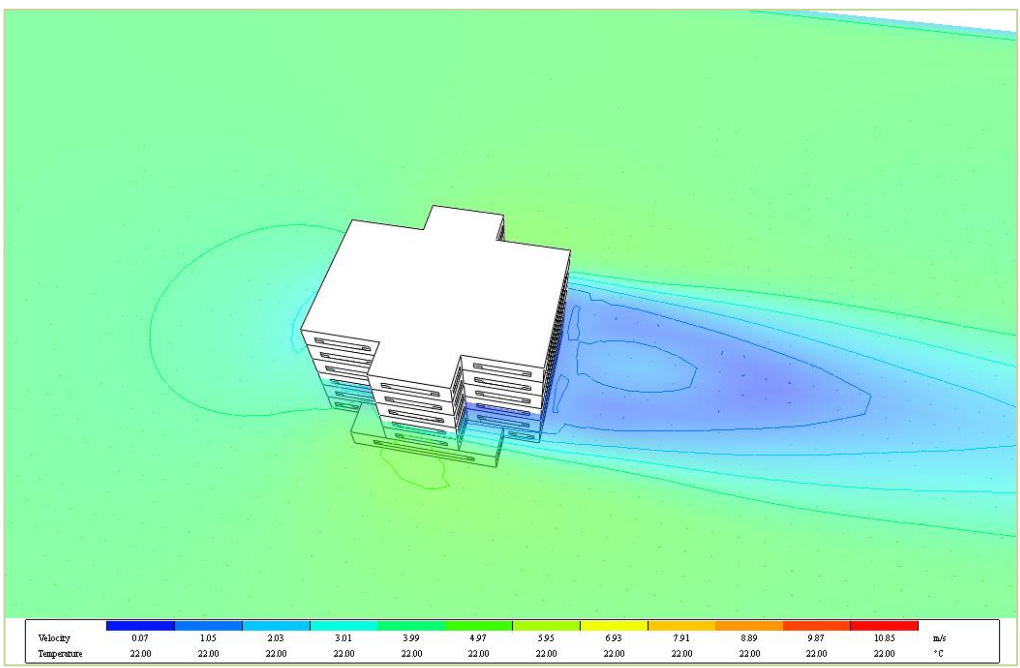
Total energy (MWh)		
COURTYARD FORM		
Date		
Jan 01-31	26.5458	
Feb 01-28	25.4345	
Mar 01-31	30.8326	
Apr 01-30	34.8198	
May 01-31	41.3632	
Jun 01-30	42.646	
Jul 01-31	45.7566	
Aug 01-31	46.2475	
Sep 01-30	42.214	
Oct 01-31	38.4703	
Nov 01-30	31.7264	
Dec 01-31	27.6231	
Summed total	433.6799	-6.90%

Total CE (kgCO2)		
	CONVENTIONAL FORM	
Date		
Jan 01-31	13152	
Feb 01-28	12868	
Mar 01-31	14779	
Apr 01-30	15837	
May 01-31	18063	
Jun 01-30	18277	
Jul 01-31	19435	
Aug 01-31	19590	
Sep 01-30	18222	
Oct 01-31	17404	
Nov 01-30	15166	
Dec 01-31	13792	
Summed total	196585	

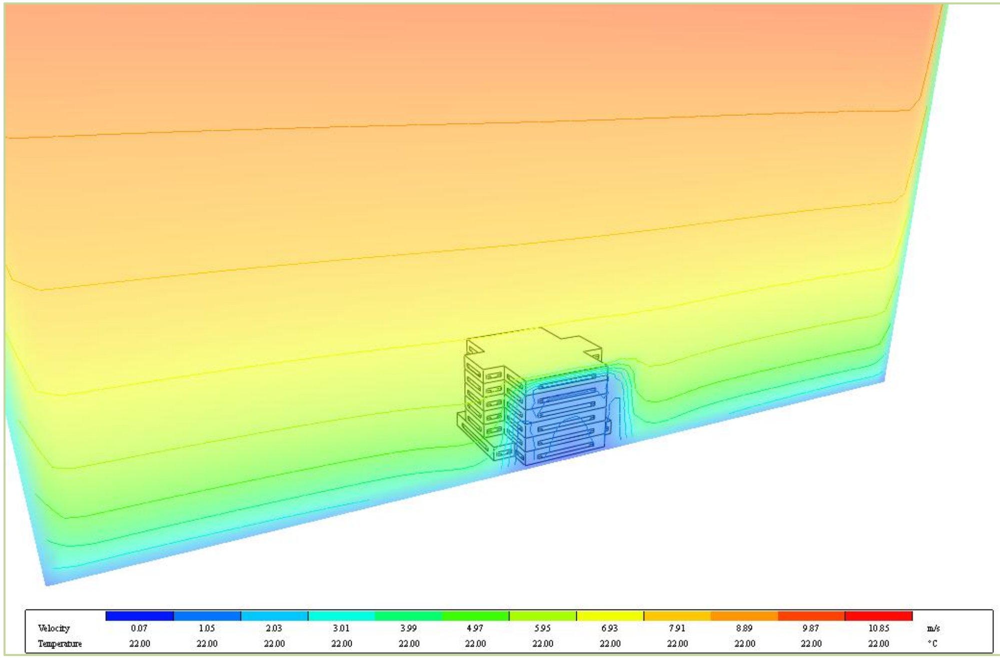
Total CE (kgCO2)		
	COURTYARD FORM	
Date		
Jan 01-31	11202	
Feb 01-28	10733	
Mar 01-31	13011	
Apr 01-30	14694	
May 01-31	17455	
Jun 01-30	17997	
Jul 01-31	19309	
Aug 01-31	19516	
Sep 01-30	17814	
Oct 01-31	16234	
Nov 01-30	13389	
Dec 01-31	11657	
Summed total	183013	-6.90%

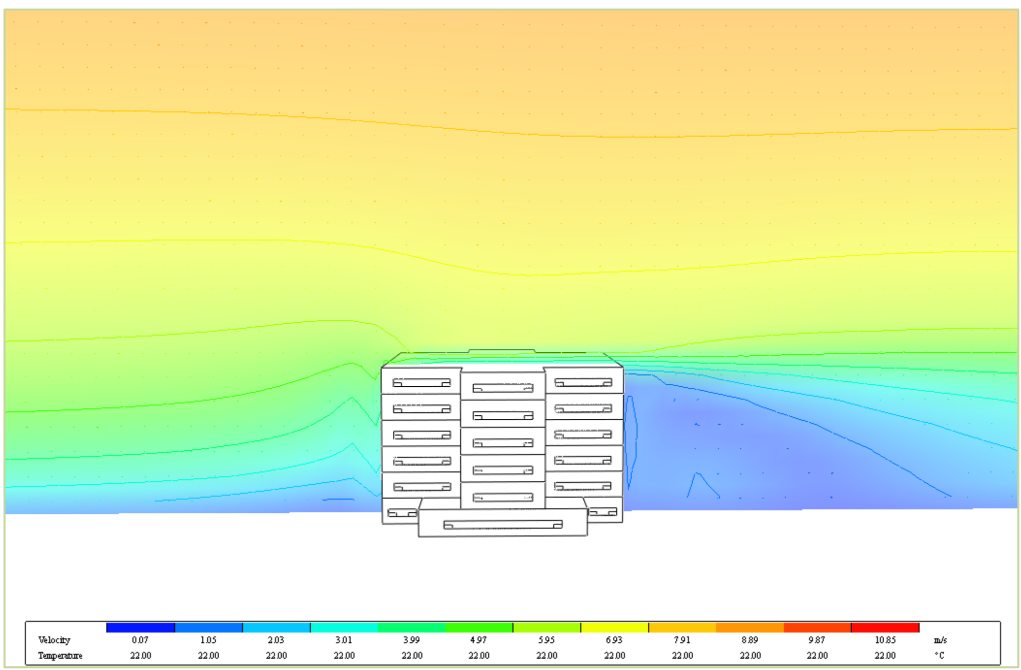
Appendix D: CFD Analysis of the conventional model





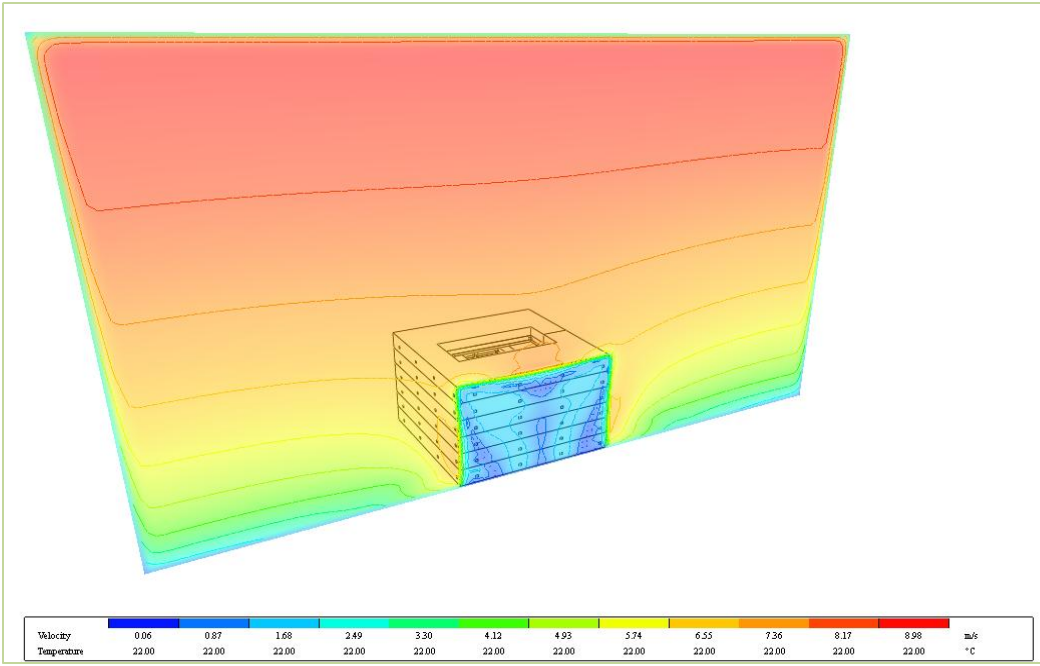
Air Velocity in the conventional model

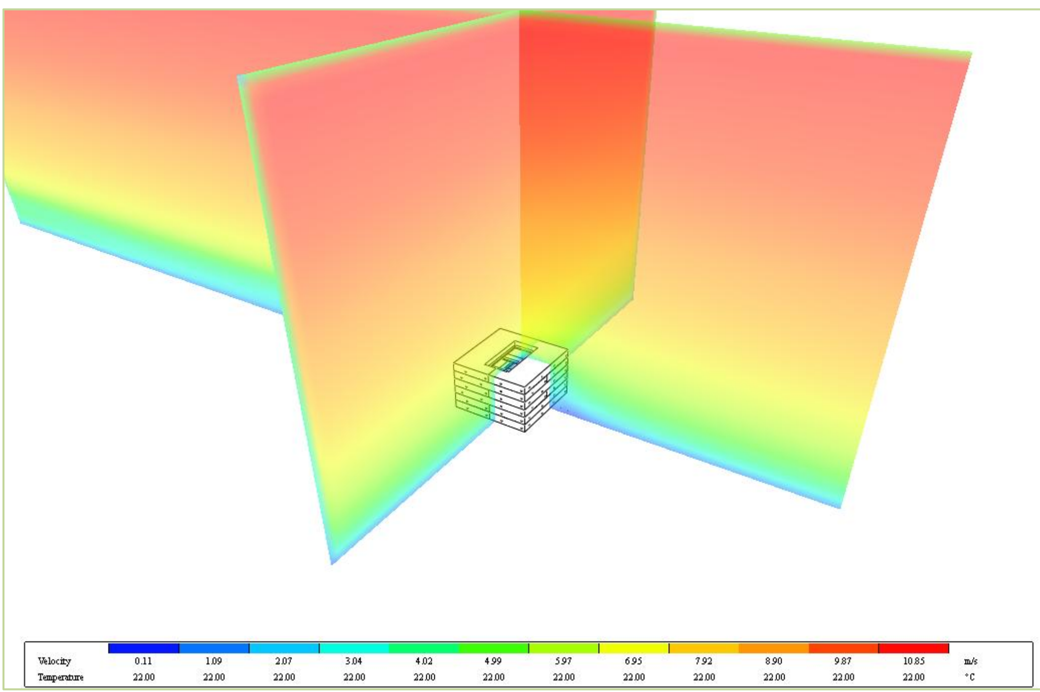




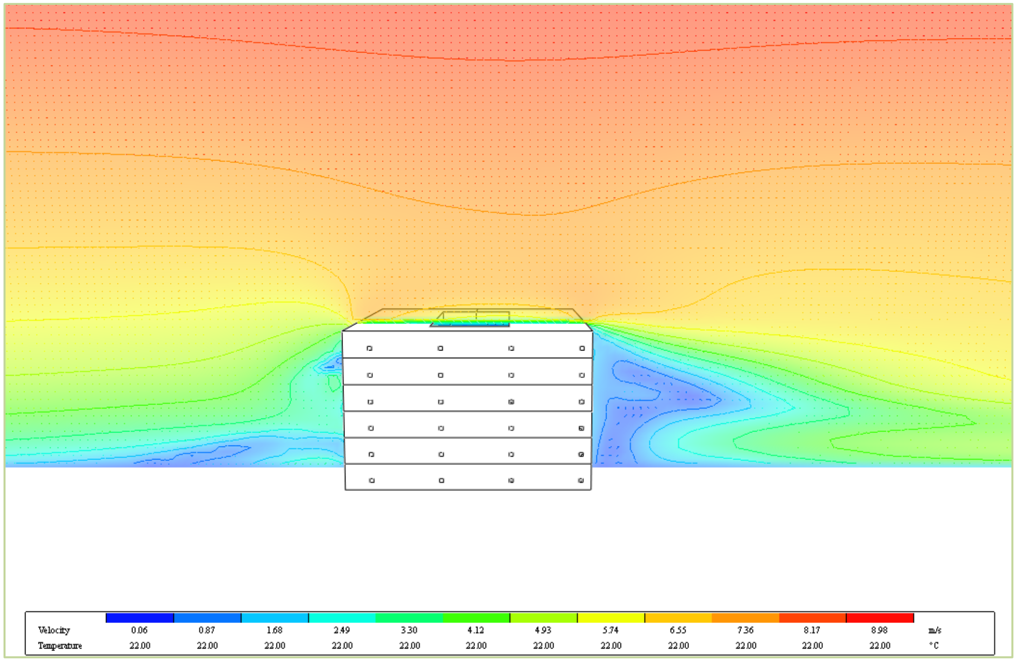
Air Velocity in the conventional model

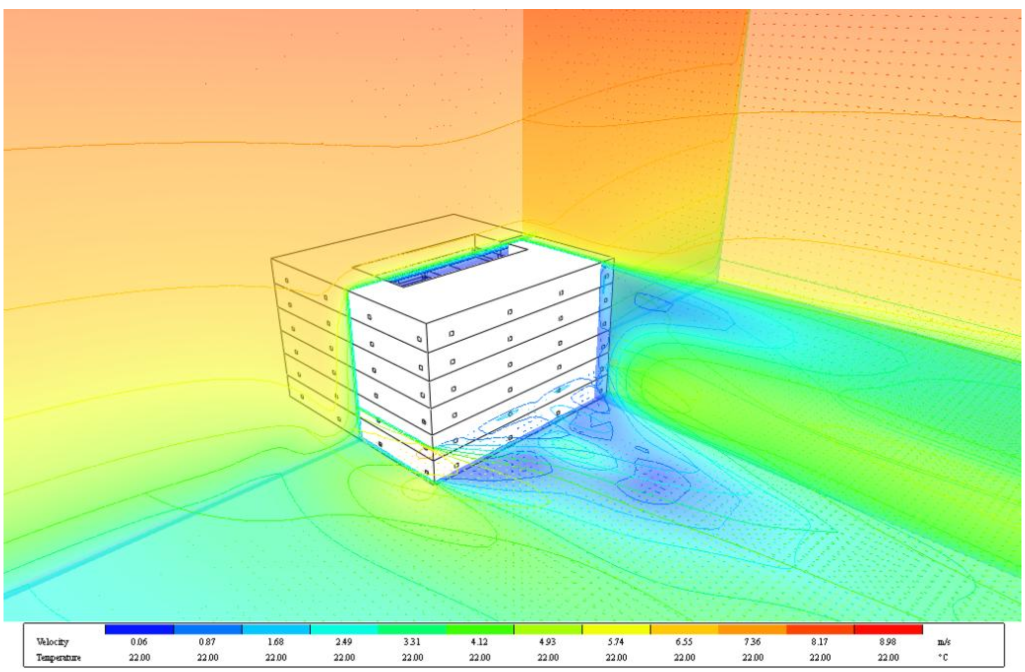
Appendix E: CFD Analysis of the courtyard model



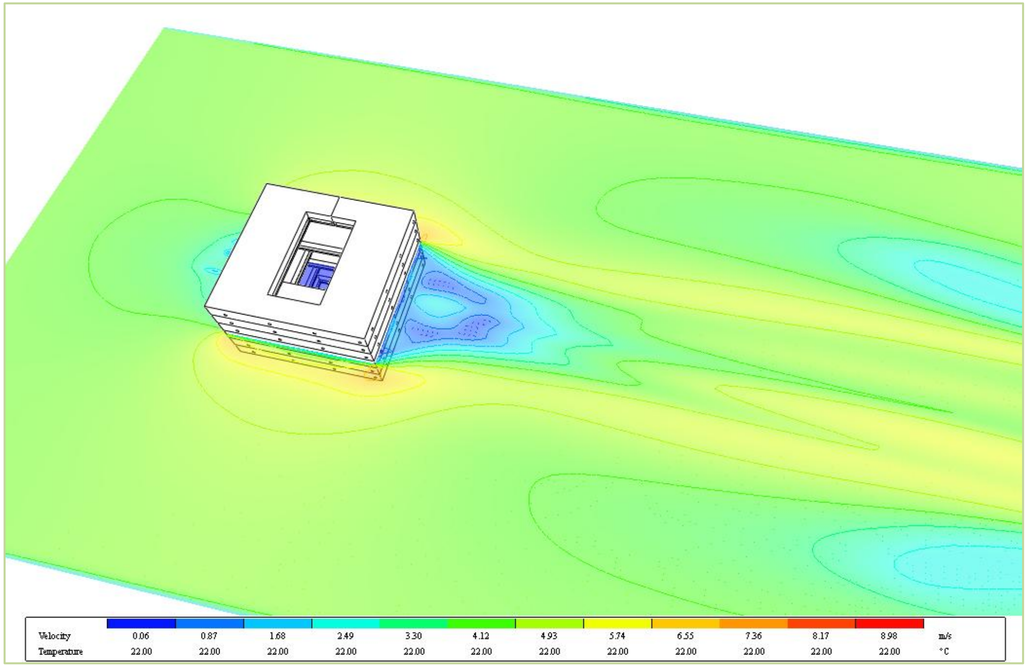


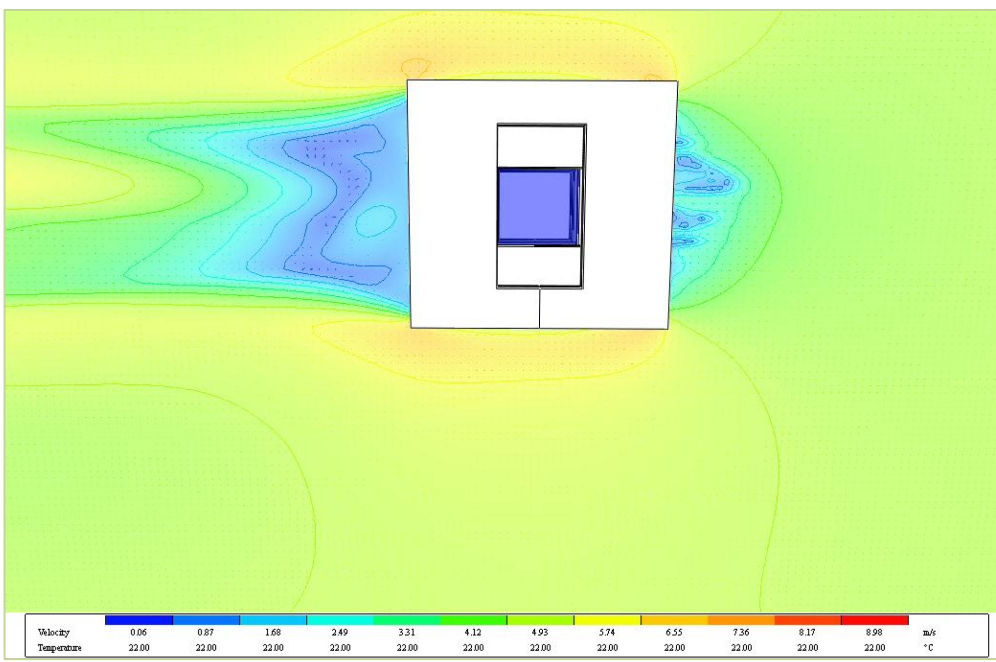
Air Velocity in the courtyard model



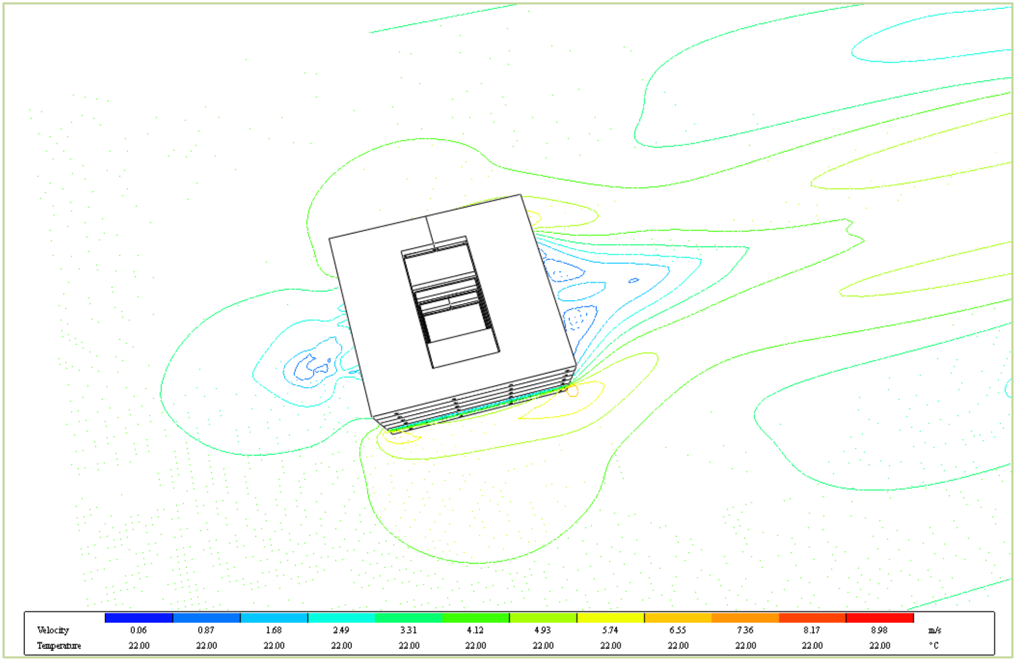


Air Velocity in the courtyard model

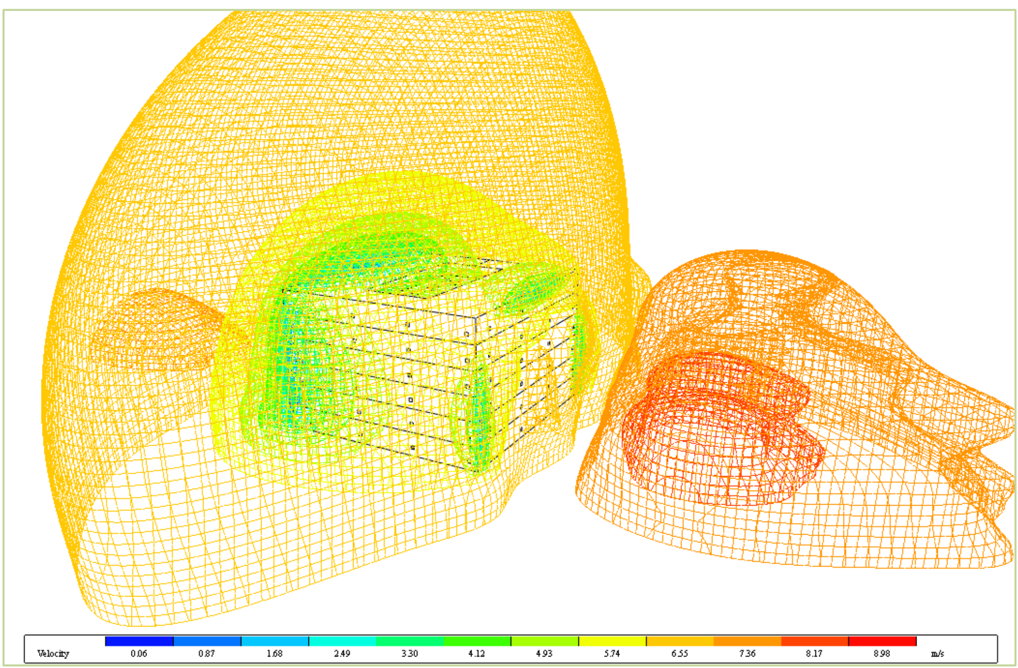




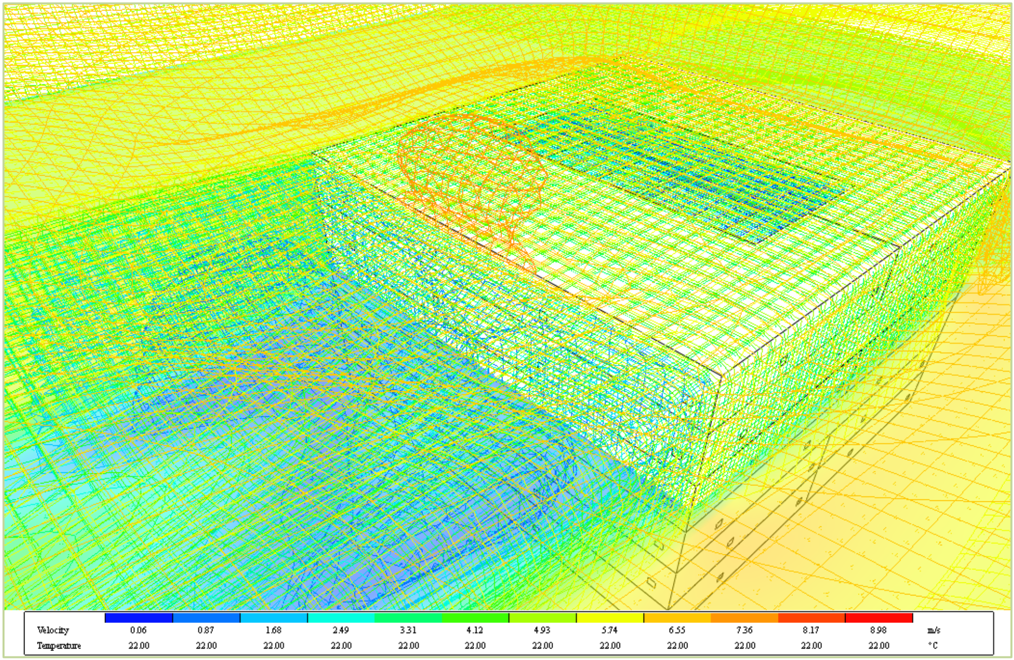
Air Velocity in the courtyard model



Air Velocity contours in the courtyard model



Air Pressure surfaces in the courtyard model



Air Velocity Surfaces in the courtyard model

Appendix F: Monthly Total Energy Calculations (ApacheSim)

Variable 1: Height in Courtyard Model

	Total energy (MWh)
	courtyard 4 levels.aps
Date	
Jan 01-31	18.1369
Feb 01-28	17.7605
Mar 01-31	21.4032
Apr 01-30	24.1494
May 01-31	28.6255
Jun 01-30	29.511
Jul 01-31	31.6233
Aug 01-31	31.9467
Sep 01-30	29.243
Oct 01-31	26.7601
Nov 01-30	22.0654
Dec 01-31	19.0854
Summed total	300.3102

	Total energy (MWh)
	courtyard 6 levels.aps
Date	
Jan 01-31	26.5458
Feb 01-28	25.4345
Mar 01-31	30.8326
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-30	42.646
Jul 01-31	45.7566
Aug 01-31	46.2475
Sep 01-30	42.214
Oct 01-31	38.4703
Nov 01-30	31.7264
Dec 01-31	27.6231
Summed total	433.6799

	Total energy (MWh)
	courtyard 8 levels.aps
Date	
Jan 01-31	35.2127
Feb 01-28	33.8217
Mar 01-31	41.0235
Apr 01-30	46.2943
May 01-31	54.8966
Jun 01-30	56.5615
Jul 01-31	60.6877
Aug 01-31	61.2662
Sep 01-30	55.9103
Oct 01-31	50.9706
Nov 01-30	42.0667
Dec 01-31	36.6923
Summed total	575.4041

	Total energy (MWh)
	courtyard 10 levels.aps
Date	
Jan 01-31	43.814
Feb 01-28	41.844
Mar 01-31	50.7955
Apr 01-30	57.3774
May 01-31	68.0715
Jun 01-30	70.1463
Jul 01-31	75.2965
Aug 01-31	76.0197
Sep 01-30	69.2781
Oct 01-31	63.1022
Nov 01-30	52.0641
Dec 01-31	45.5236
Summed total	713.3329

Appendix G: Monthly Total Energy Calculations (ApacheSim)

Variable 2: Glazing Type in Courtyard Model

	Total energy (MWh)
	courtyard single glazed.aps
Date	
Jan 01-31	26.5944
Feb 01-28	25.6475
Mar 01-31	32.1085
Apr 01-30	38.6278
May 01-31	48.3015
Jun 01-30	50.6546
Jul 01-31	54.8487
Aug 01-31	55.5726
Sep 01-30	49.7846
Oct 01-31	43.5009
Nov 01-30	33.7143
Dec 01-31	27.6991
Summed total	487.0545

	Total energy (MWh)
	courtyard double glazed.aps
Date	
Jan 01-31	26.5458
Feb 01-28	25.4345
Mar 01-31	30.8326
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-30	42.646
Jul 01-31	45.7566
Aug 01-31	46.2475
Sep 01-30	42.214
Oct 01-31	38.4703
Nov 01-30	31.7264
Dec 01-31	27.6231
Summed total	433.6799

	Total energy (MWh)
	courtyard triple glazed.aps
Date	
Jan 01-31	26.5271
Feb 01-28	25.224
Mar 01-31	30.4187
Apr 01-30	34.0278
May 01-31	40.1204
Jun 01-30	41.2619
Jul 01-31	44.2109
Aug 01-31	44.6745
Sep 01-30	40.8886
Oct 01-31	37.5138
Nov 01-30	31.2411
Dec 01-31	27.5054
Summed total	423.6143

Appendix H: Monthly Total Energy Calculations (ApacheSim)

Variable 3: Wall Thickness in Courtyard Model

	Total energy (MWh)
	courtyard 15cm.aps
Date	
Jan 01-31	26.5585
Feb 01-28	25.5581
Mar 01-31	30.9142
Apr 01-30	35.0079
May 01-31	41.6711
Jun 01-30	42.9596
Jul 01-31	46.1725
Aug 01-31	46.6656
Sep 01-30	42.5908
Oct 01-31	38.7269
Nov 01-30	31.8178
Dec 01-31	27.6517
Summed total	436.2946

	Total energy (MWh)
	courtyard 20cm.aps
Date	
Jan 01-31	26.5445
Feb 01-28	25.4598
Mar 01-31	30.8483
Apr 01-30	34.8853
May 01-31	41.4853
Jun 01-30	42.7752
Jul 01-31	45.9349
Aug 01-31	46.4278
Sep 01-30	42.3804
Oct 01-31	38.5764
Nov 01-30	31.7485
Dec 01-31	27.6176
Summed total	434.684

	Total energy (MWh)
	courtyard 25cm.aps
Date	
Jan 01-31	26.5458
Feb 01-28	25.4345
Mar 01-31	30.8326
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-30	42.646
Jul 01-31	45.7566
Aug 01-31	46.2475
Sep 01-30	42.214
Oct 01-31	38.4703
Nov 01-30	31.7264
Dec 01-31	27.6231
Summed total	433.6799

	Total energy (MWh)
	courtyard 30cm.aps
Date	
Jan 01-31	26.5422
Feb 01-28	25.3874
Mar 01-31	30.7973
Apr 01-30	34.7235
May 01-31	41.1582
Jun 01-30	42.4496
Jul 01-31	45.5027
Aug 01-31	46.0097
Sep 01-30	42.0245
Oct 01-31	38.3566
Nov 01-30	31.6894
Dec 01-31	27.6369
Summed total	432.278

	Total energy (MWh)
	courtyard 40cm.aps
Date	
Jan 01-31	26.5418
Feb 01-28	25.3353
Mar 01-31	30.7224
Apr 01-30	34.5572
May 01-31	40.7824
Jun 01-30	42.0829
Jul 01-31	45.0435
Aug 01-31	45.59
Sep 01-30	41.6944
Oct 01-31	38.1669
Nov 01-30	31.6381
Dec 01-31	27.6736
Summed total	429.8287

Appendix I: Monthly Total Energy Calculations (ApacheSim)

Variable 4: Insulation Material in Courtyard Model

	Total energy (MWh)
	courtyard- EPS.aps
Date	
Jan 01-31	26.5458
Feb 01-28	25.4345
Mar 01-31	30.8326
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-30	42.646
Jul 01-31	45.7566
Aug 01-31	46.2475
Sep 01-30	42.214
Oct 01-31	38.4703
Nov 01-30	31.7264
Dec 01-31	27.6231
Summed total	433.6799

	Total energy (MWh)
	courtyard- glass fiber.aps
Date	
Jan 01-31	26.5216
Feb 01-28	25.3508
Mar 01-31	31.0991
Apr 01-30	35.822
May 01-31	43.25
Jun 01-30	44.9245
Jul 01-31	48.4383
Aug 01-31	49.0078
Sep 01-30	44.4916
Oct 01-31	39.9985
Nov 01-30	32.3533
Dec 01-31	27.6109
Summed total	448.8684

	Total energy (MWh)
	courtyard- phenolic foam.aps
Date	
Jan 01-31	26.5213
Feb 01-28	25.3483
Mar 01-31	31.0985
Apr 01-30	35.8221
May 01-31	43.2496
Jun 01-30	44.9254
Jul 01-31	48.4383
Aug 01-31	49.0084
Sep 01-30	44.4921
Oct 01-31	39.9993
Nov 01-30	32.354
Dec 01-31	27.6105
Summed total	448.868

	Total energy (MWh)
	courtyard- cavity ashrae.aps
Date	
Jan 01-31	26.5125
Feb 01-28	25.2938
Mar 01-31	31.5897
Apr 01-30	37.5175
May 01-31	46.4356
Jun 01-30	48.762
Jul 01-31	52.9504
Aug 01-31	53.6513
Sep 01-30	48.3231
Oct 01-31	42.5712
Nov 01-30	33.4134
Dec 01-31	27.653
Summed total	474.6735

	Total energy (MWh)
	courtyard- cellular polyurethane.aps
Date	
Jan 01-31	26.5706
Feb 01-28	25.481
Mar 01-31	30.7315
Apr 01-30	34.4277
May 01-31	40.6258
Jun 01-30	41.7534
Jul 01-31	44.7066
Aug 01-31	45.1662
Sep 01-30	41.3217
Oct 01-31	37.8709
Nov 01-30	31.4801
Dec 01-31	27.6467
Summed total	427.7821

Appendix J: Monthly Total Energy Calculations (ApacheSim)

Variable 5: Insulation Thickness in Courtyard Model

	Total energy (MWh) courtyard- 25mm insulation.aps
Date	
Jan 01-31	26.5151
Feb 01-28	25.3206
Mar 01-31	31.2527
Apr 01-30	36.3769
May 01-31	44.2934
Jun 01-30	46.1832
Jul 01-31	49.9186
Aug 01-31	50.5315
Sep 01-30	45.7489
Oct 01-31	40.8425
Nov 01-30	32.7004
Dec 01-31	27.6203
Summed total	457.304

	Total energy (MWh) courtyard 50mm insulation.aps
Date	
Jan 01-31	26.5458
Feb 01-28	25.4345
Mar 01-31	30.8326
Apr 01-30	34.8198
May 01-31	41.3632
Jun 01-30	42.646
Jul 01-31	45.7566
Aug 01-31	46.2475
Sep 01-30	42.214
Oct 01-31	38.4703
Nov 01-30	31.7264
Dec 01-31	27.6231
Summed total	433.6799

	Total energy (MWh) courtyard- 75mm insulation.aps
Date	
Jan 01-31	26.601
Feb 01-28	25.5173
Mar 01-31	30.6606
Apr 01-30	34.1476
May 01-31	40.0978
Jun 01-30	41.1154
Jul 01-31	43.955
Aug 01-31	44.3926
Sep 01-30	40.6834
Oct 01-31	37.4429
Nov 01-30	31.3048
Dec 01-31	27.6724
Summed total	423.5908

	Total energy (MWh) courtyard- 100mm insulation.aps
Date	
Jan 01-31	26.6595
Feb 01-28	25.574
Mar 01-31	30.5689
Apr 01-30	33.7742
May 01-31	39.3935
Jun 01-30	40.2627
Jul 01-31	42.9507
Aug 01-31	43.3586
Sep 01-30	39.8306
Oct 01-31	36.8709
Nov 01-30	31.071
Dec 01-31	27.7191
Summed total	418.0336

Appendix K: Monthly Total Energy Calculations (ApacheSim) Conventional, Courtyard (A) and Courtyard (B) Models

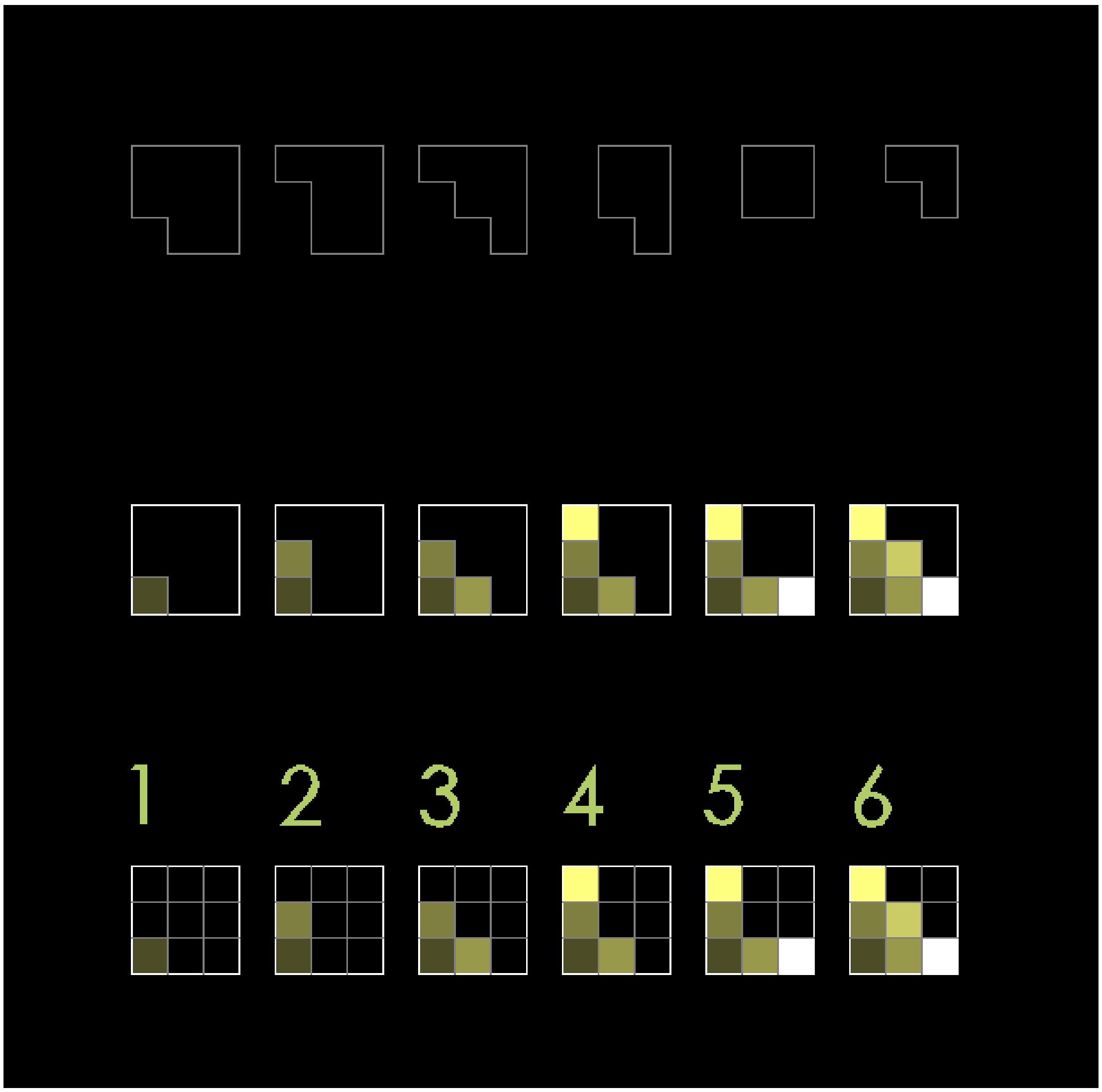
Total energy (MWh)		
	CONVENTIONAL FORM	
Date		
Jan 01-31	31.1658	
Feb 01-28	30.4935	
Mar 01-31	35.0205	
Apr 01-30	37.5289	
May 01-31	42.8035	
Jun 01-30	43.3114	
Jul 01-31	46.0554	
Aug 01-31	46.4209	
Sep 01-30	43.1789	
Oct 01-31	41.2413	
Nov 01-30	35.9394	
Dec 01-31	32.6833	
Summed total	**465.8427**	

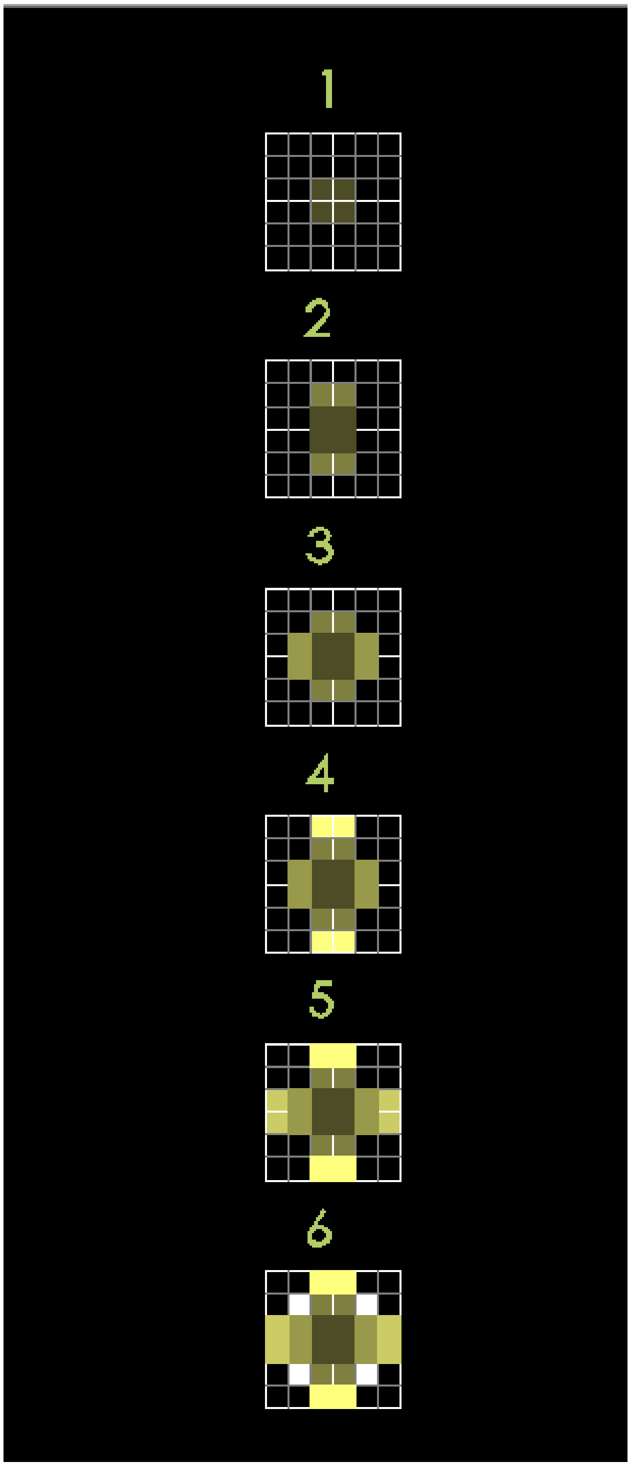
Total energy (MWh)		
	COURTYARD FORM A	
Date		
Jan 01-31	26.5458	
Feb 01-28	25.4345	
Mar 01-31	30.8326	
Apr 01-30	34.8198	
May 01-31	41.3632	
Jun 01-30	42.646	
Jul 01-31	45.7566	
Aug 01-31	46.2475	
Sep 01-30	42.214	
Oct 01-31	38.4703	
Nov 01-30	31.7264	
Dec 01-31	27.6231	
Summed total	433.6799	-6.90%

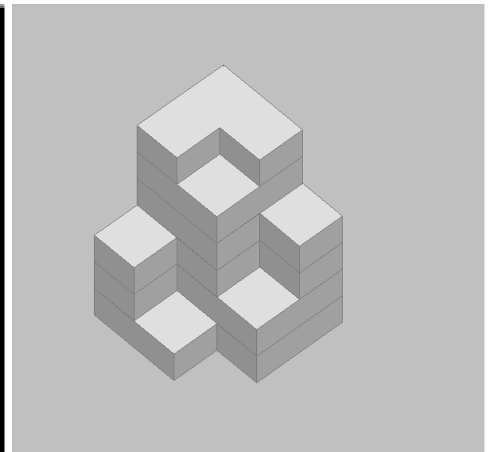
Total energy (MWh)		
COURTYARD FORM B		
Date		
Jan 01-31	26.6844	
Feb 01-28	25.5558	
Mar 01-31	30.4846	
Apr 01-30	33.4911	
May 01-31	38.8304	
Jun 01-30	39.6329	
Jul 01-31	42.1905	
Aug 01-31	42.6043	
Sep 01-30	39.2164	
Oct 01-31	36.4752	
Nov 01-30	30.9233	
Dec 01-31	27.7889	
Summed total	413.8778	-11.16%

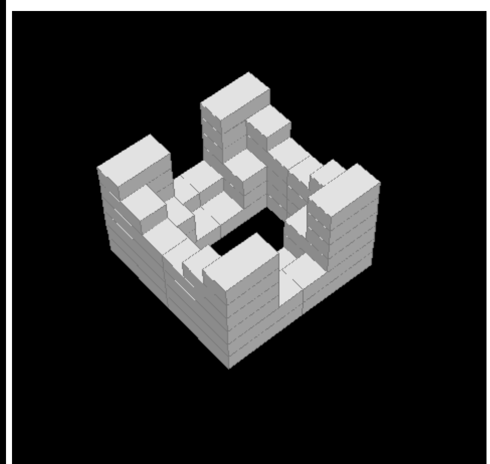
Appendix L: Recommendations (Proposal 1)

A proposal has been designed to overcome the lack of privacy by dynamically manipulating the courtyard shapes and configuration in each floor, so that a better privacy can be achieved. Furthermore, this configuration satisfies the inhabitants' need for individuality in their connection with nature, while enjoying better microclimates. The figures include the model evolution and schematic concept of this proposal.









Top right: the block unit

Bottom right: the model

Left: floor plans, lighter green stands for higher courtyard.

Appendix M: Recommendations (Proposal 2)

This propsal is designed to offer an increasing courtayrd area along the building's height, which results in a varied floor plate in each floor, along with more dynamic section of the courtyard. This might be advantagous to enhance the airflow movement into the courtayrd and around the building hence improving the stack effect ventilation. An environmental evaluation of this proposal would be recommended in order to weigh expected advantages against its energy saving behavior.