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Comparative Analysis Of Daylight In Conventional And Courtyard Houses Of Lahore, Pakistan

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A B S T R A C T:
Daylight is one of the renewable sources whose appropriate use can affect many factors such as occupant well-being, energy loads, heating and cooling demands etc. It is the amount of daylight entering the building which may affect the energy loads as well as the occupants of the buildings. The major aim of this present research is to compare the daylight availability in one-kanal conventional and courtyard houses in Lahore. Moreover, to investigate the optimum value of daylighting levels required in both housing typologies and to estimate the degree of correlation between the required courtyard opening ratio and glazing ratios. The study conducted is simulation-based and has been carried out on Ecotect software. After the conduction of multiple simulations, optimal values have been provided for better daylighting levels in one-kanal conventional and courtyard houses of Lahore.

K E Y W O R D S: *Daylight, Courtyard house, Conventional house, Conventional house, Daylight factor.*

1. Introduction

Making social and technological progress has been cardinal to man since the dawn of time. Mankind has consistently made an effort to improve their living conditions. (Sheykhi, 2002) From living in caves, for shelter, to living in mansions powered by technology, modern man has achieved what could have only been imagined a hundred years ago. (Gillio, et al., 2019) (Mishra, 2019)But in this battle of evolution, humans have conveniently ignored the role of their natural environment. (Mishra, 2019) (Chu & Karr, 2013) The unchecked and unsustainable use of natural resources, especially non-renewable energy resources has immensely strained the intricate ecology of the planet and has led to what can only be called an “environmental emergency”. (Chu & Karr, 2013) (Lee, et al., 2021) .

One of the steps towards energy-efficient buildings is the incorporation of an appropriate amount of daylight as it leads to the minimized use of artificial light and reduced [1]electricity costs (Piotrowska & Borchert, 2017). Daylight is not only a matter of internal amenity, energy efficiency, health and well-being but also of long-term energy and cost savings. (Piotrowska & Borchert, 2017) (Reffat & Ahmad, 2020) According to Pakistan's economic survey data, the household sector's electricity consumption has been growing at a pace of 2% annually. (Alvi, et al., 2022.11)

In our construction industry architects, builders and other stakeholders do not consider the fenestration design seriously, they place the windows according to the ongoing trend or what appeals aesthetically to them but we should design windows according to our climate of Lahore (Hasan, 2022) (Ahmed, 2016). The main aim of this research is to compare the daylight availability in one kanal[2] conventional and courtyard house in Lahore and to find appropriate glazing ratios of the same category.

2. Materials and Methods

This research is mainly a comparative analysis of the daylight performance of two different types of housing typologies practised in Lahore. It analyzes whether conventional and

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courtyard houses constructed in the same area can give different or the same daylight performances. For this purpose, previous studies regarding courtyard performances in daylight were reviewed and analyzed through a literature review. Some of the data regarding energy consumption and window-to-floor area ratio has also been collected through a literature review. Based on the secondary data collected, an experiment based on computer simulations was conducted on Ecotect software. (see figure 1)

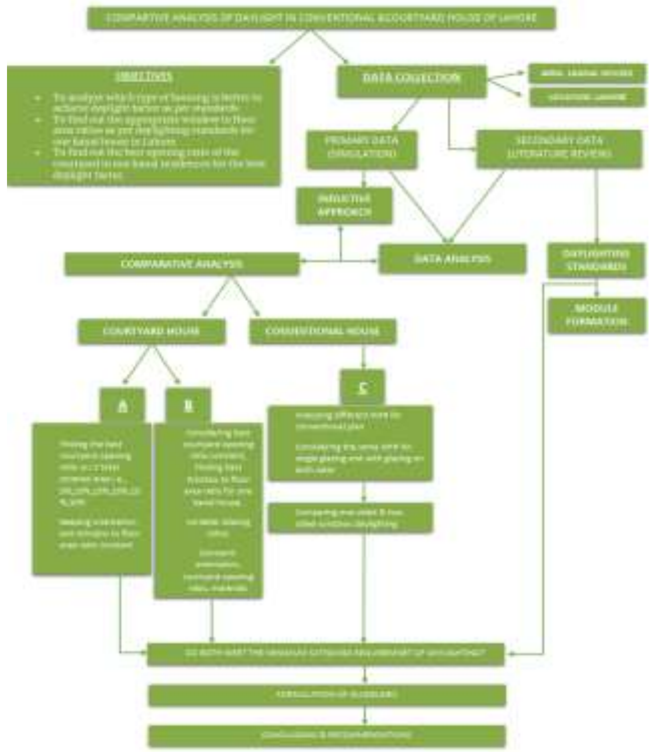


Figure 1: Methodology

The experiment analyzed whether the incorporation of the courtyard enhanced or degraded the daylight performance or whether the results were the same. Moreover, appropriate Window to floor area ratios (WFR) were found for conventional and courtyard houses through simulations which were compared with the average daylight standards calculated. (See section 2.2) The comparative analysis method was used to study the simulation results. In this paper by conventional we mean the type of houses which have been constructed in the past two decades without a courtyard, incorporating by-laws, following any architectural style. By WFR we mean window to floor area ratio and WWR means window to wall area ratio.

The focus of the study was mainly on the impact of conventional and courtyard houses on daylight performance. The sample size of the research was only limited to one kanal[3] house i.e., 4500 square feet.

2.1. Literature Review

"Daylighting'' is the natural light available inside. (Alrubaih, et al., 2013), naturally lit buildings save energy and cost (Krasić, et al., 2013), achieving the required levels. (Eleanor S. Lee, 2022)The primary performance indicator for daylight intensity is the daylight factor. The ratio of internal illumination at a point to instantaneous exterior illumination on a horizontal surface under a cloudy sky is known as the "daylight factor." Despite variations in the amount of external illumination, the daylight factor does not change. (Yee Mee, 2021)

[3] Area of one kanal is equal to 4500 square feet. Most of the plots in Lahore have a rectangular cutting so dimensions of one kanal house are around 50 feet by 90 feet

Daylight Factor (D.F) = Ei / Ee * 100 (1)

where Ei =illuminance due to daylight at a point on the indoor working plane, Eo = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of an overcast sky

windows being the key element (MALAYSIA, 2017) is more susceptible to climate change. The U-value and solar irradiance determine the heat flow (Lu, et al., 2015). Window-to-wall area ratio (WWR) results in excessive daylight in the building. The recommended range of WWR is 10 to 12.5% while (Guthrie, 2003) suggested it to be 10 to 25%. (Jamaludin, et al., 2015) In typical rooms, the maximum limit of WFR to avoid over-lit spaces is 25% whereas WFR less than 10% provided sufficient daylight levels. (Nedhal, et al., 2016)

(Al-Masri & Abu-Hijleh, 2012) evaluated the environmental performance of residential buildings and courtyards in Dubai's hot, arid climate. For energy and daylighting courtyard houses performed well in all seasons to typical layouts. The study incorporated conventional and courtyard buildings, later conventional was converted into a courtyard layout, and found a 6.9% reduction in energy use, and performed well for daylight. (Samir, et al., 2017) investigated the effectiveness of daylighting in various building types in hot, arid climates using simulation. He took 6 types of models which included monolithic buildings, courtyard buildings with 1, 2 and 3-storey conventional buildings. The first one was the comparison of 2 storeys courtyards and conventional building types. (See Fig.2)

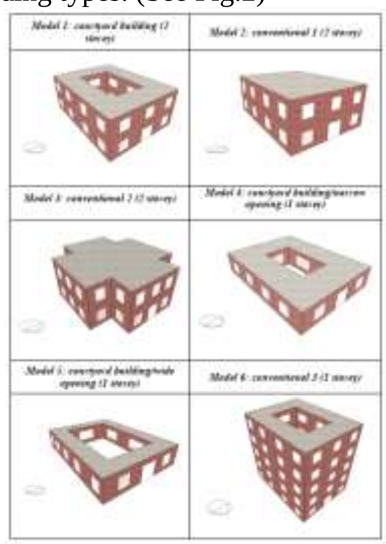


Figure 2: Tested building models,Source: (Samir, et al.,

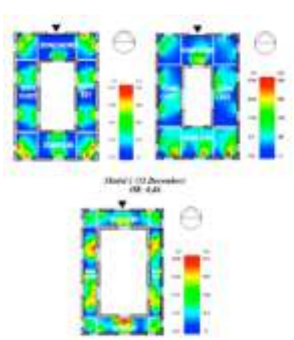


Figure 3: The relationship between courtyard opening

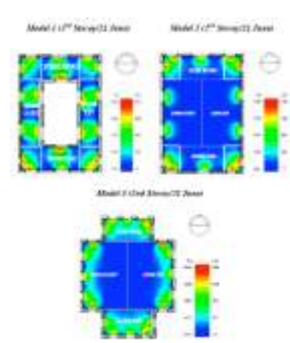


Figure 4: Illumination levels / D.F of three models Source: (Samir, et al., 2017)

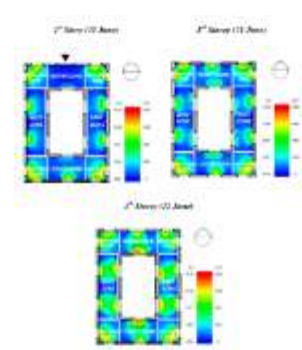


Figure 5: Effect of courtyard depth on the

Upon comparative analysis, it was seen that courtyard building illuminance levels were beyond 500 lux which means that it was better than the conventional ones. The second analysis was the depth analysis in which it was seen that the deeper the courtyard, the lesser the illuminance level of the storey closer to the ground. (See Fig.5) Courtyard models were tested with different opening ratios such as (0,25), (0,66), and (0,50). It was seen that the greater the opening ratios more were the illuminance levels. (See Fig.3-5)
A study was carried out in Dubai by (Al Masri, 2010) in which he incorporated courtyards in midrise residential
, the courtyard design requires less use of passive methods like shading devices and light shelves because the average daylight factors of 6.3% and 5.6% for the winter and summer days, respectively, are near the USGBC recommended daylight factor level of 5%. (See Fig.6,7,8)

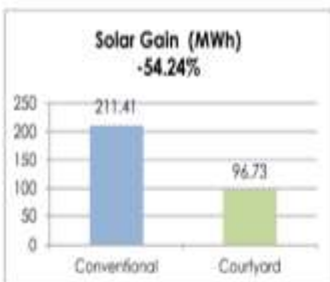


Figure 6: Solar gain in conventional & courtyard forms

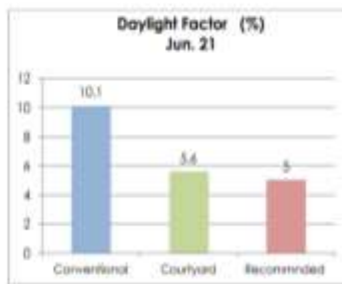


Figure 7: Daylight factors in both models compared to recommended-Jun-21 *Source: (*

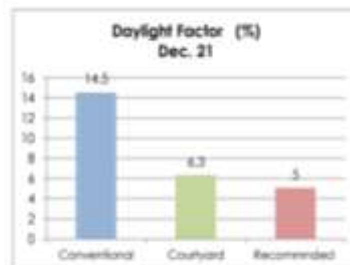


Figure 8: Daylight factor in both models compared to recommended-Dec 21

The impact of courtyard design on energy efficiency and natural light in homes in Toronto's cold climate was investigated by (Vaisman & Horvat, 2018). The primary findings indicated that internal courtyards might increase illumination hours from 9% to 20%.
(Tan, et al., 2016) studied the effect of the length and width of the courtyard on daylighting performance in residential buildings. The location selected was Hubie, China with a composite climate. The findings indicate that improved lighting illuminance is found in courtyards with a height-to-width ratio lesser than 1. No benefit was found for height-to-width ratios greater than 5.
(Soflaei, et al., 2017) investigated for the best courtyard models in terms of thermal comfort and concluded that square courtyards are better than rectangular ones in hot dry climates. (Guedouh, et al., 2019) concluded that deep courtyards are perfect for solving problems in hot and arid regions.
(Toris-Guitron, et al., 2022) determined the effect of orientation and proportion on the thermal comfort of the courtyard. Upon simulation-based research, it was concluded that as courtyard width and length increase, solar heat gains and ventilation rates also increase. In courtyards where the long axis was oriented E-W, heat gains were reduced, and ventilation rates increased when the long axis was oriented NW-SE.
As reviewed by (Toris-Guitron, et al., 2022), In comparison to a squared courtyard plan with an aspect ratio of 1:1, Almhafdy et al. found that a plan aspect ratio of 1:2 (Width/Length), which is a rectangle with a length twice the width, has higher air velocities and better thermal performance.
(YOUSUF et al., 2016) conducted experimental research on the daylight intensity of Cantonment cottages of Multan. The sample size taken was 5 and 7 Marla houses, the results

were compared with the CIBSE guide standards and it was concluded that the daylight factor was higher than the standard values as window openings were larger.

2.2 Average Daylight Factor Calculation:

Several countries have made daylighting regulations for the proper incorporation of daylight in spaces. Some of them are mentioned below. (See Table 1)

Table 1: Daylighting standards of different regions

Region	Daylight standards	Design sky illuminance
Malaysia	Minimum WFR 15% Minimum D.F Not Less Than 2% Average Illumination Levels 206 Lux	18500 Lux
UK	2% Average Daylight Factor	4000 Lux
Dubai	WFR 10% Min. Min. 150 Lux	
Japan	D.F 1% Illuminance Levels 150 Lux	
US	Min. D.F 2%	5000 Lux
Australia	Min WFR 10% Thumb Rule: Window Design 20% Of the Room Floor Area Minimum Daylight Factor Of 1% For 90% Of the Floor Area	10000 Lux

As there are no appropriate daylighting standards for Pakistan, so to calculate the daylighting levels, we have to calculate the average standards by taking an average of daylight factors of the above-mentioned daylight factors (See table 1) which is around 1.7% or 153 lux.

Table 2: Literature review summary

AUTHOR	TOPIC	FINDINGS
(Nedhal, et al., 2016)	Relationship between window-to-floor area ratio and single-point daylight factor in varied residential rooms in Malaysia	In typical rooms the maximum limit of WFR to avoid overlit spaces is 25% whereas WFR is less than 10% provided sufficient daylight levels)
(Al Masri, 2010)	Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate. Renewable and sustainable energy	Evaluated the environmental performance of residential buildings was concluded that courtyard buildings performed between than the conventional ones, they offer more usable light 6.9% reduction in energy consumption was found.

(Samir, et al., 2017)17)	Daylight efficiency prediction of courtyard vs. Conventional building models using simulation tool under specific climate conditions.	Illuminance levels of conventional and courtyard buildings in hot, arid climates were compared and it was concluded that courtyard buildings' illuminance levels were more than 500 lux i.e., better than the conventional ones. Moreover, as the depth of the courtyard increases the illuminance levels decrease. The greater the opening ratios more were the illuminance levels.
(Tayari & Nikpour, 2022)i	Investigated on daylight quality of the central courtyard's adjacent rooms in traditional houses in the hot dry region of Iran	The results of this study showed that traditional homes' surrounding rooms can all attain work plane illuminance levels that are above acceptable levels.
(Al Masri, 2010)	Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate. Renewable and sustainable energy	Courtyard buildings outperformed, average daylight factors of 6.3% and 5.6% for the winter and summer days, respectively, and are near to the USGBC recommended daylight factor level of 5%.
(Taleghani , et al., 2014)	Indoor thermal comfort in urban courtyard block dwellings in the Netherlands	The thermal performance of the courtyard was tested with various orientations in the Netherlands N-S and E-W orientations provided the least and most comfortable environments.
(Vaisman & Horvat, 2018)	Influence of internal courtyards on the energy load and hours of illuminance in row houses in Toronto	Research conducted in Toronto indicated that the courtyard might increase the illumination hours from 9 to 20%.
(Muhaisen & Gadi, 2006)	Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome	courtyard forms in residential buildings in Rome, Italy were analysed w.r.t the effect of solar gains on heating and cooling loads. It was concluded that deeper courtyard forms performed well for the cooling load in summer and heating load in winter.
(Tan, et al., 2016)	The influence of the courtyard geometry on passive lighting energy savings	studied the effect of the length and width of the courtyard on daylighting performance in residential buildings in Hubie, China. The findings indicate that improved lighting illuminance is found in courtyards with a height-to-width ratio lesser than 1. No benefit was found for height-to-width ratios greater than 5.
(Soflaei, et al., 2017)	Socio-environmental sustainability in traditional courtyard houses of Iran and China	investigated for the best courtyard models in terms of thermal comfort and concluded that square courtyards are better than rectangular ones in hot dry climates.
(Guedouh, et al., 2019)	Passive strategy based on courtyard building morphology impact on thermal and luminous	concluded that deep courtyards are perfect for solving problems in hot and arid regions.

	environments in the hot and arid region	
(Toris-Guitron, et al., 2022)	Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate	It was concluded that as courtyard width and length increase, solar heat gains and ventilation rates also increase. In courtyards where the long axis was oriented E-W, heat gains were reduced, and ventilation rates increased when the long axis was orientated NW-SE.
(Toris-Guitron, et al., 2022)	Evaluation of the thermal performance of traditional courtyard houses in a warm humid climate	Rectangular plan courtyards have better performance than squared plan courtyards.
(Yousuf, et al., 2017)	Evaluation of daylight intensity for sustainability in residential buildings in cantonment cottages Multan	As the size of the opening increases the daylight factor also increases.

The statistical data required to understand the relationship of window sizing with respect to the window-to-floor area ratio (WFR) in the context of Lahore was not studied before. The percentage of glazing required to meet the daylighting standards was not investigated. Observations were there that the incorporation of a courtyard improved the daylighting but the exact sizing /percentage of windows which can be provided to achieve the standards were missing.

3. Simulation Models

This research was conducted in four steps. First, one kanal prototype, following both Lahore Development Authority (LDA)[4] and Defence Housing Authority (DHA) bye-laws[5] of conventional houses were created. Leaving the mandatory open spaces according to bye-laws the permissible covered area was divided into four zones. These models were simulated on Ecotect to find the best WFR according to the average standards calculated. Two types of simulations were carried out for a conventional house

i. Simulation with one single window
ii. Simulation with two-sided windows

[4] LDA(Lahore development Authority) major bye-laws for one kanal residences includes leaving of mandatory open space from one side and rear of the plot

[5] DHA (Defense housing Authority) major bye laws for one kanal houses included leaving 5 feet open space from all three sides of the plot and 15 feet from the front ,leaving all the mandatory spaces you can then construct in the leftover space.

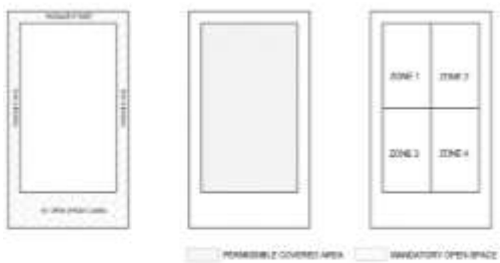


Figure 9:DHA conventional house

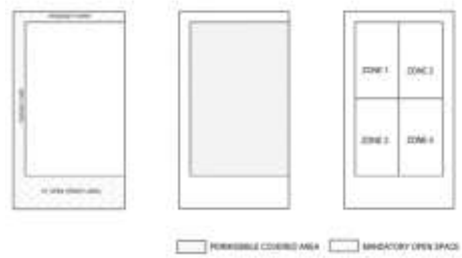


Figure10: LDA conventional house

As this is simulation-based research so software used were Ecotect and AutoCAD. Ecotect software has been used for the simulations. This procedure contains three main steps:

- Model design
- Setting up for the simulation
- Simulation output

In the second step, prototypes were created containing a central courtyard following DHA and LDA bylaws and dividing the rest of the space into four zones.

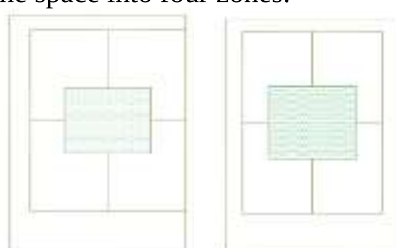


Figure 11: Central courtyard incorporation in LDA & DHA prototype

In the third step both types of prototypes in Figure 11, courtyard ratios with respect to the permissible covered areas were calculated and modelled. Then each model was simulated on Ecotect to find the best opening ratio of the courtyard with reference to daylighting.6 different models of each housing were simulated to find out the best courtyard opening ratio. (see Figure 12,13)

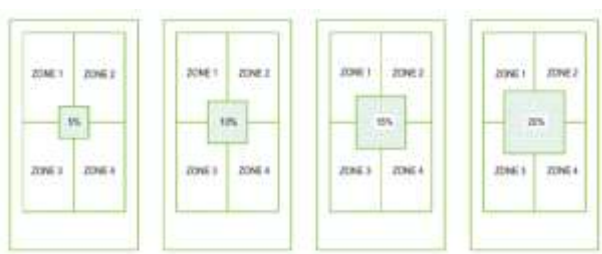
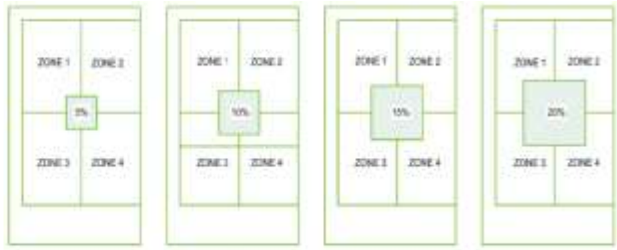
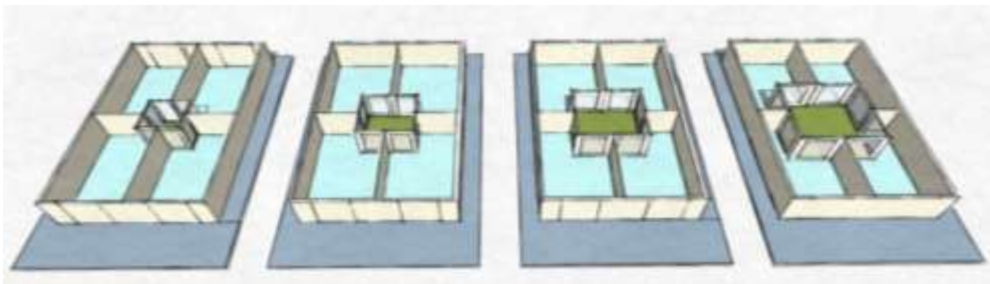


Figure12: Courtyard Percentage in DHA

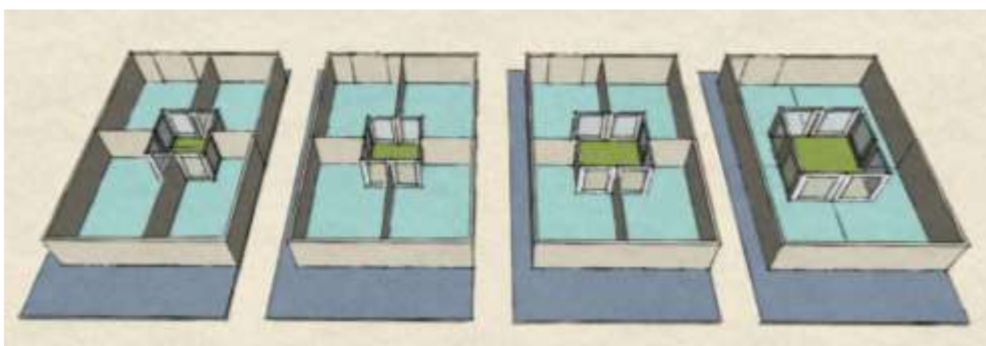
Figure 13: Courtyard Percentage in LDA





5% COURTYARD OF THE PERMISSIBLE COVERED AREA	10% COURTYARD OF THE PERMISSIBLE COVERED AREA	15% COURTYARD OF THE PERMISSIBLE	20% COURTYARD OF THE PERMISSIBLE COVERED AREA

Figure 14: 3-dimensional view of courtyard opening ratios following DHA bye-laws (Source: Author)



5% COURTYARD OF THE PERMISSIBLE COVERED AREA	10% COURTYARD OF THE PERMISSIBLE COVERED AREA	15% COURTYARD OF THE PERMISSIBLE	20% COURTYARD OF THE PERMISSIBLE COVERED AREA

Figure15: 3-dimensional view of courtyard opening ratios following LDA bye-laws Source: Author

3.1 Simulation Setting

The location was set in Lahore, Pakistan. The daylight simulation was performed in overcast sky conditions which is the worst condition for daylight availability. (Kensek and Jae ,2011)

Table 3: The constant variables of the site during simulation conditions

SITE LOCATION	LAHORE, PAKISTAN
LATITUDE	31.5

LONGITUDE	74.3
PROJECT TYPE	Residential
SKY CONDITIONS	Overcast sky (9000 lux) (June, Sep/Mar, December, 12.00 pm)

According to the Green Building Council daylight is measured at 800mm from the floor level which is around 2 feet and 6 inches (Al-Obaidi et al., 2013) and simulations were carried out at 2 feet. Numerous parameters such as building height, glazing type, wall thickness, and courtyard style were taken constant. The study was varied across two parameters, the first one was the number of windows and the second one was the courtyard opening ratio but not simultaneously.

3.2 Simulation process

The simulation process involved three phases after modelling. The first phase involves Conventional house Simulation for best Window-to-floor area ratios according to standards for DHA & LDA prototypes. The second phase consists of a Courtyard house simulation for best opening ratios for central courtyards. The last phase houses Courtyard house simulations for the best window-to-floor area ratios with the best opening ratios calculated in the previous step.(see Figure 16)

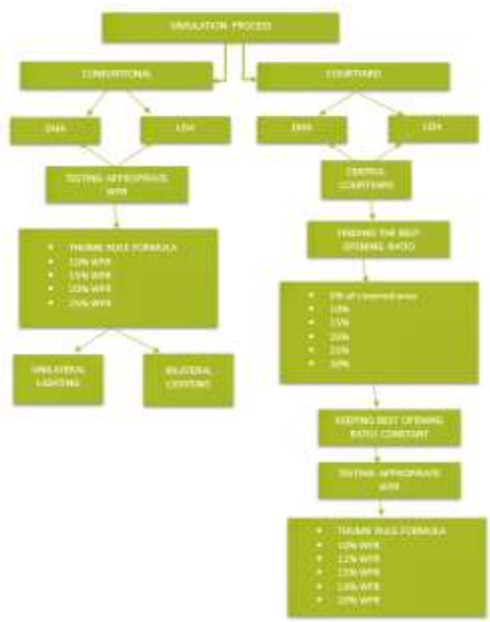


Figure 16: Flowchart for simulation

4. Results for Conventional House Design

According to the results deduced from the simulations it has been analyzed that a 20% glazing ratio is found to be the optimum value (See Table 4) for the single window with DHA bye-laws as it lies close to the average standard values calculated whereas for two-sided windows with DHA bye-laws 15% glazing ratio is found to have the optimum value. (See Table 5)
In the case of LDA bye-laws results for single-window and two-sided windows are found to be 10% and 15% respectively. (See table 6 & 7)

Table 4: Daylight analysis with single window incorporating DHA bye-laws

WFR/ glazing ratio of each zone in a	Simulati on	Result

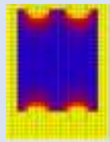
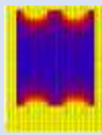
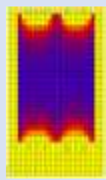
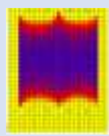
permissible covered area		
10% WFR		44% of the floor area as a daylight factor of less than 1percent.whereas only 16% of the floor area has a daylight factor of 1.5% to 2%.
15% WFR		41% of the floor area has a daylight factor ranging from 0 to 1.5% whereas 26% of the floor area has a daylight factor of 1.5 to 2% and 32% of the space has a daylight factor of 2 and above.
20% WFR		19% of the floor area has a daylight factor of 1 to 1.5% whereas 34% of the space has a daylight factor ranging from 1.5 to 2%,18.5% of the space has a daylight factor between 2 to 3% AND 28% of the space has a daylight factor of 28%.
25% WFR		Almost 50% of the space has a daylight factor of more than 4%

Table 5: Daylight Analysis with Two-sided Window

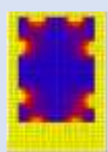
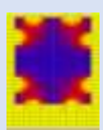
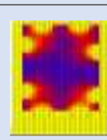
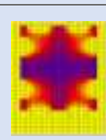
Wfr/ Glazing Ratio Of Each Zone In Permissible Covered Area	Simulation	Analysis
10% WFR		Avg value 35.68% 36% of the space has a d.f of less than 1% whereas 28% of the space has a daylight factor between 1 to 1.5% and 28% has a .f of 2% and above.
15% WFR		39% of the floor area has a daylight factor of less than 1% whereas 42% of the space has a daylight factor ranging from 1.5 to 2%and 19% of the space has a daylight factor of 2 and above values
20% WFR		Too much glare has been observed as 45% of the floor area has a daylight factor of 2 and above values whereas only 23% of the space meets the average daylight standard values.
25% WFR		More than 50% of the space has a daylight factor of around 6%.

Table 6: Daylight analysis with a single window in LDA bye-laws

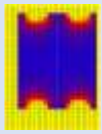
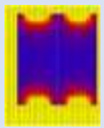
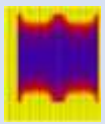
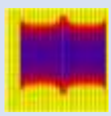
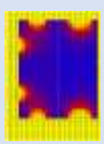
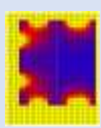
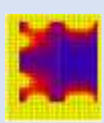
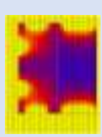
Wfr/ glazing ratio of each zone in a permissible covered area	Simulation	Analysis
10% WFR		Around 60% of the space has a daylight factor of less than 1% which is very low than the optimum value
15% WFR		40% of the space has a d.f of 1% whereas 35% has a d.f between 1.5% to 2% and 28% has a df of 2% and above.
20% WFR		45% of the space has a d.f of 1.5 to 25 and 57% of the floor area has a daylight factor of 2% and above.
25% WFR		Too much glare has been observed

Table 7: Daylight Analysis with two-sided window with LDA bye-laws

Wfr/ glazing ratio of each zone in a permissible covered area	Simulation	Results
10% WFR		Around 40% of the space has a D.F. of less than 1% whereas **35%** of the space has a daylight factor between 1-2% and the rest of the 25% has a D.F. of 2% and above.
15% WFR		50% of the space has a d.f of 2% and above whereas 14% space has a daylight factor between 1 to 1.5% and 36% of the space has a d.f in between 1.5 to 2%.
20% WFR		50% of the space has a D.F. of more than 4% which is much higher than the standards.
25% WFR		65% of the space has a D.F. of more than 4% which is much higher than the standards.

5. Results for Courtyard House

Simulations were carried out with the incorporation of the courtyard in the same covered area as that of a conventional house. The courtyard analysis was conducted for the 5%,10%,15%, and 20% courtyard areas out of the permissible covered area of the house. Each courtyard area was tested against the same window-to-floor area ratios (WFR) as in the conventional prototype house.

5.1 5% Central Courtyard of The Permissible Covered Area with DHA Bye-Laws

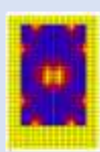
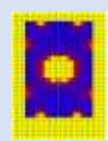
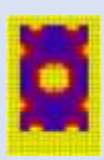
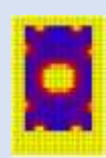
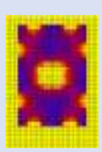
For the 5% courtyard of the permissible covered area, the zone area for each zone was reduced from that of conventional ones. So, each zone was taking around 648.21 sq. ft area. The 5% area of the courtyard in square feet was 136.64 sq. Ft. Along with normal simulations in which 50% of the glazing was allotted to the windows facing permissible open space and 50% to the courtyard, a special case has also been observed with 70% glazing allotted towards the courtyard and 30% towards the permissible open spaces of the plot to analyze the differences in both the cases with same courtyard and window areas.

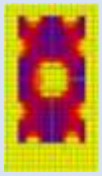
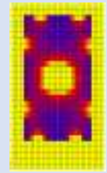
Table 8: Area calculation with 5% courtyard

Total permissible covered area	2732.78 sq. ft
5% Courtyard	136.64sq.ft
Zone area	648.21sq.ft

It has been concluded that for 5% courtyard area of the permissible covered area, 15% WFR is appropriate for each zone as it hardly meets the average standards calculated which are 153lux or 1.7% daylight factor whereas in the case of special edition where 70% of the glazing ratio is allotted to the courtyard area and 30% to the perimeter windows the appropriate WFR is achieved at 20%.In this case, 46% of the zone area has a 2% or less than 2, daylight factor whereas 25% of the space has 1% daylighting levels and 14% has a daylight factor of 3% and 15% has a daylight factor of 4% and above but this percentage lies only in the areas closer to the windows. When compared to the normal case the special consideration uses more WFR but lighting distribution is much better in this case. (See table 9)

Table 9: WFR analysis with 5% courtyard of the permissible covered area

Window-to-floor area ratio (WFR)	Simulation	Analysis	Special consideration
10% WFR OF EACH ZONE (64.821 SQ.FT)		35% of the zone is receiving 2% of the D.F. where whereas 65% is receiving 0 to 1% daylight which is below the average standards calculated.	
15% WFR OF EACH ZONE (97.23 SQ.FT)		17% of the space receives 1% D.F whereas 34% of the space receives 2%daylight,5% has 3% whereas 33% of the zone closer to the window has a D.F of 4%	
20%WFR OF EACH ZONE (129.64 SQ.FT)		75% of the space has a D.F of 2 to 3% whereas 15% has a d.f of 1%	

25% OF EACH ZONE (162 SQ.FT)		Almost 85% of the space receives a D.F of 3 TO 4 PERCENT rest of the 15% has a D.F of 2%.	

5. 2 10% Central Courtyard of The Permissible Covered Area with DHA Bye-Laws

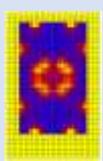
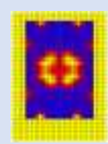
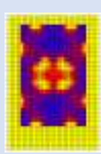
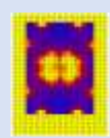
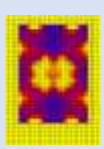
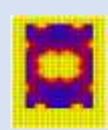
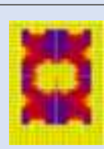
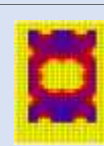
For 10% central courtyard following are the areas calculated below. (See table 10)

Table 10: Area calculation with 10% courtyard

Total permissible covered area	2732.78 sq. ft
10% Courtyard	273.27sq.ft
Zone area	614.21sq.ft

It has been concluded that for 10% courtyard area of the permissible covered area, 15% WFR is appropriate for each zone as 42% of the space receives daylight between 1_2% which is close to the standards calculated I.e., 153lux or 1.7% daylight factor. In the case of the special edition 20%WFR meets the average standards with uniform light 47% of the space receives daylight between 1_2% and only 2% of the zone area is left where there is a daylight factor of 0%. (See Table 11)

Table 11: WFR analysis with 10 % courtyard of the permissible covered area

Window-to-floor area ratio (WFR)	Simulation	Analysis	Special consideration
10% WFR OF EACH ZONE		30% of the space has a daylight factor of 0% and there is a non-uniform distribution of light in each zone.	
15% WFR OF EACH ZONE		10% of the space receives 0% D.F., whereas 15% of the space has 1% D.F. 75% of the space receives 2 to 2.5% daylight and 5% of the space closer to the window has 4% daylight factor.	
20%WFR OF EACH ZONE		24% of the space has a D.F OF 2% whereas 64% has a D.F of 3% and 12% of the space has a D.F of 4%	
25% OF EACH ZONE		Almost 60% of the space has a D.F. of 4% and the rest 40% lies from 2 to 3%.	

5.3 15% Central Courtyard of The Permissible Covered Area with DHA Bye-Laws

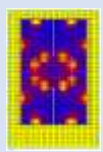
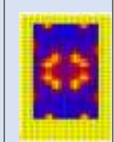
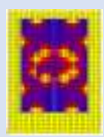
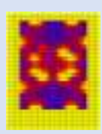
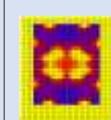
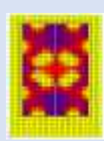
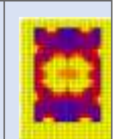
For 15% central courtyard following are the areas calculated below. (See table 12)

Table 12: Area calculation with 15% courtyard

Total permissible covered area	2732.78 sq. ft
15% Courtyard	409.91ft
Zone area	580.7 sq. ft

For 15% courtyard of the total permissible covered area appropriate WFR in the normal and special cases is 15% as in both cases 40 & 39% of the space is receiving daylight factor in between 1_2% respectively but the more uniform distribution of light is seen in normal case. (See Table 13)

Table 13: WFR analysis with 15 % courtyard of the permissible covered area

Window-to-floor area ratio (wfr)	Simulation	Analysis	Special consideration
10% WFR OF EACH ZONE		45% of the spaces receive hardly any light.	
15% WFR OF EACH ZONE		40% of the space receives daylight between 1-2% whereas 8% of the space receives no light and 10% of the space receives 3% daylight and 25% of the space closer to the windows has a daylight factor of 4% & above	
20%WFR OF EACH ZONE		40% of the space has a D.F OF 3%,15% has 2 to 1% and the rest of the space closer to the glazing areas has a D.F of 4 to 5%.	
25% OF EACH ZONE		The values lie over the optimum values	

5.4 20% Central Courtyard of The Permissible Covered Area with DHA Bye-Laws

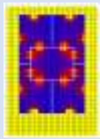
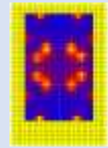
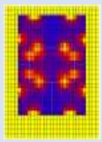
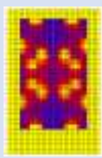
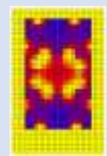
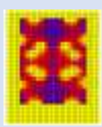
For 20% central courtyard following are the areas calculated below. (See table 14)

Total permissible covered area	2732.78 sq. ft
20% Courtyard	546.551ft
Zone area	546.7sq. ft

Table14: Area calculation with 20% courtyard

On average, each zone should have a daylight factor of 1.7 % i.e., 153 lux according to the climate of Lahore. For 20% courtyard of the permissible covered area, 15 % WFR was found appropriate meeting the optimum values. In the case of the special edition, 20% of the glazing ratio was found to meet the standards as 36% of the space had a daylight factor of 2%. (See Table 15)

Table 15: WFR analysis with 20% courtyard of permissible area

Window-to-floor area ratio (wfr)	Simulation	Analysis	Special consideration
10% WFR OF EACH ZONE		19% of the space receives no daylight whereas 45% has only 1% D.F & only36% has 2% D.F	
15% WFR OF EACH ZONE		39% of the space has a daylight factor between 1-2% whereas 6% of the spaces receive no light which is in the extreme corners and 17% of the space closer to the windows have a daylight factor of 4 % and higher	
20%WFR OF EACH ZONE 		40% of the space receives a d.f of 3% whereas 20% has a d.f of 2%,10% of the space is receiving 1%d.f, remaining 30% has a d.f ranging from 4 to 5%.	
25% OF EACH ZONE		The values lie over the optimum values.	

5.5 5% Central Courtyard of The Permissible Covered Area with LDA Bye-Laws

For the 5% central courtyard following are the areas calculated below. (See table 16)

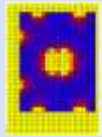
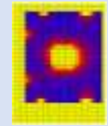
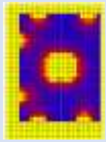
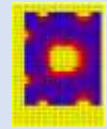
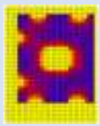
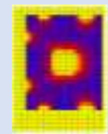
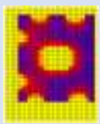
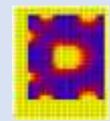
Table 16: Area calculation for 5% courtyard area

Total permissible covered area	3088.98 sq. ft
5% Courtyard	154.4 sq. ft
Zone area	733.63 sq. ft
Area left after the incorporation of a courtyard	2934.53 sq. ft

For a 5% courtyard area and permissible covered area of 2934.53 sq. ft appropriate WFR which is close to the standards is 15%. In the case of the special edition, the appropriate WFR which is close to the optimum value is 20%, in which 55% of the space receives 1 to 2% daylight and only 5% of the space has a daylight factor of zero but it is only in the corners of the space. (See Table 17)

Table 17: WFR analysis with 5% courtyard following LDA bye-laws

Window-to-floor area ratio (wfr)	Simulation	Analysis	Special consideration

10% WFR OF EACH ZONE		50% of the space is receiving a D.F of 0%. 	
15% WFR OF EACH ZONE		35% of the space has a D.F. of 2%, and 14% of the space has a D.F. ranging from 0.5 to 1%. The rest of the space closer to the glazing has a D.F. from 3 to 4%.In short 54.5% receive a daylight factor of 1 to 2%.	
20%WFR OF EACH ZONE		10% of the space has a D.F of 1% where whereas 30% of the space has a D.F of 2 to 3% and the rest of the space closer to the windows D.F ranges from 4 to 5%.	
25% OF EACH ZONE		In the right part average daylight is 2.5% and in the left part, it is 3.5% which are 225 and 315 lux respectively.	

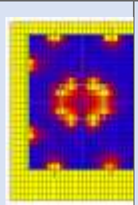
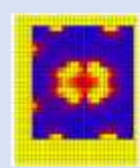
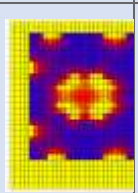
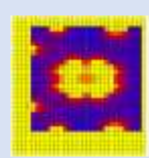
5.6 10% Central Courtyard of The Permissible Covered Area with LDA Bye-Laws
For 10% central courtyard following are the areas calculated below. (See Table 18)

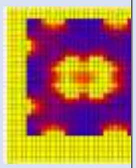
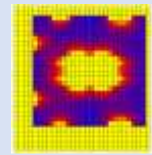
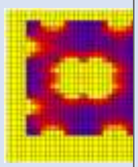
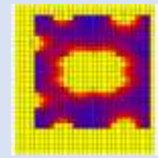
Total permissible covered area	3088.98 sq. ft
10% Courtyard	308.89sq. ft
Zone area	695 sq. ft
Area left after the incorporation of the courtyard	2780sq. ft

Table18: Area calculation for 10% courtyard area

For a courtyard of 10% of the permissible covered area, spaces with a single window along with the courtyard require 20% WFR whereas Spaces with two-sided windows along with the courtyard require 15% WFR and has a daylight factor of 2%. (See Table 19)

Table 19: WFR analysis with 10% courtyard following LDA bye-laws

Window-to-floor area ratio (wfr)	**Simulation**	**Analysis**	**Special consideration**
10% WFR OF EACH ZONE		Only 0.5 to 1% daylight is entering the space which is too little than the average standard which is 1.7% or 153 lux.	
15% WFR OF EACH ZONE		60% of the space is having D.F of 2%,5% of the space has 0% D.F whereas 15% space has a D.F of 1% rest of the area closer to the windows has a D.F of 4 to 5%.	

20%WFR OF EACH ZONE 		50% of the space has a D.F of 3% whereas 20% has D.F 2% and the remaining 30% has a D.F of 4%.	
25% OF EACH ZONE		More than 50% of the space has a D.F ranging between 4 to 7%, so the space is overlit.	

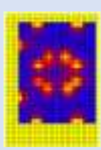
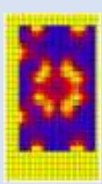
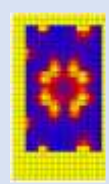
5.7 15% Central Courtyard of The Permissible Covered Area with LDA Bye-Laws
For 15% central courtyard following are the areas calculated below. (See Table 20)

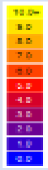
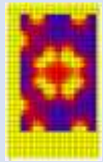
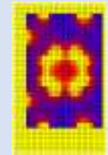
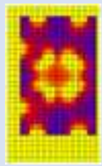
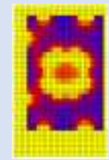
Table 20: Area calculation for 15% courtyard area

Total permissible covered area	3088.98 sq. ft
15% Courtyard	463.35sq. ft
Zone area	656 sq. ft
Area left after the incorporation of the courtyard	2625sq. ft

For a courtyard of 15% of the permissible covered area, the optimum value of daylight is achieved with a 15% WFR or glazing ratio. (See Table 21)

Table 21: WFR analysis with 15% courtyard following LDA bye-laws

Window-to-floor area ratio (WFR)	Simulati on	Analysis	Special consideration
10% WFR OF EACH ZONE		Only 0.5% daylight is entering the space which is too little than the average standard which is 1.7% or 153 lux. Almost 40% of the space has a D.F 0%.	
15% WFR OF EACH ZONE		In the left portion of the plan, almost 45% of the space has a D.F of 2%, whereas 25% of the space has a D.F of 1% and the rest of the 30% of the space closer to the windows has a D.F of 4.5%. As the left portion is exposed to 3 windows and the right one to 2 windows so there is a difference in the D.F. of both portions. In the right portion, 30% of the space has a D.F of 1% whereas 5% has a 0% D.F mostly in the corners of the zone,20% of the space has a D.F of 15 to 2% and the rest of the 50% area has a D.F of 3 to 5% closer to the windows.	

20%WFR OF EACH ZONE 		In the left part, 40% of the space area has a D. F of 1.5 to 2%, whereas 30% has a D. F of 3% and the rest of the 30% areas closer to the glazing has a D. F of 4 to 5%. In the right part of the plan, 60% of the space has a D.F of 2% whereas 20% of the space has a D.f of 1% and the rest of the 20% space closer to the windows have a D.F of 4 to 5%.	
25% OF EACH ZONE		In the left part of the plan, almost 45% of the space has a D.F of 3 to 4% which is much higher than the optimum values. In the right portion of the plan, 60% of the space has a D.F. of 2 to 2.5% whereas areas closer to the glazing have a D.F. of 4 to 5%.	

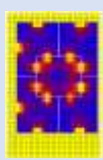
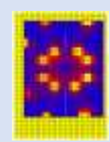
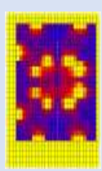
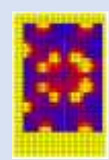
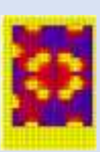
5.8 20% Central Courtyard of The Permissible Covered Area with LDA Bye-Laws
For 20% central courtyard following are the areas calculated below. (See table 22)

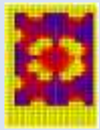
Table 22: Area calculation for 20% courtyard area

Total permissible covered area	3088.98 sq. ft
20% Courtyard	617.79sq. ft
Zone area	617.79sq. ft
Area left after the incorporation of the courtyard	2471.19 sq. ft

For a courtyard of 20% of the permissible covered area, the optimum value of daylight is achieved with a 15% WFR or glazing ratio. (See Table 23)

Table 23: WFR analysis with 20% courtyard following LDA bye-laws

Window-to-floor area ratio (wfr)	Simulation	Analysis	Special consideration
10% WFR OF EACH ZONE		40% of the space covers 2 percent daylight whereas 18% of the space has no daylight and 18% of the space closer to the windows has a d.f of 4%and 1% of the space has 1% daylight. But in the right-hand side zone of the plan, 25% of the space has 0 percent daylight factor.	
15% WFR OF EACH ZONE 		On the extreme corners, only 1% of the space is where no daylight can reach whereas the rest of the 65% of space has a D.F of 1.5 to 2%.35% of the space closer to the windows has a daylight factor ranging between 3 to 5 whereas on the right side of the plan as the glazing part is lesser so almost 30 percent of the space daylight factor ranges from 0 to 1%.	
20%WFR OF EACH ZONE		On the left-hand side of the plan, daylighting levels are extremely high ranging from 3 to 5% almost in the 50% area whereas in the right side of the plan, almost 65% of the area has a d.f of 2%.	

25% OF EACH ZONE		Daylighting levels are quite higher than the standards to be achieved.	

5.9 Results Summary

The following are the results deduced from the computer simulation analysis.

Table 24: summarized results of conventional-form houses

	Total covered area Sq. Ft	Permissible covered area Sq. Ft	Zone area Sq. Ft	Glazing ratio with a single window	Glazing ratio with two-sided window
DHA	4500	2732.78	455.46	20%	15%
LDA	4500	3088.98	510.71	20%	15%

Table 25: Courtyard form results following DHA bye-laws

Permissible covered area Sq. Ft	Courtyard area in %age	Courtyard area in (Sq. Ft)	Zone area (Sq. Ft)	Glazing ratio (%age)	Special edition (%age)
2732.78	5%	136.64	648.21	15% (97 sq. Ft)	20%
2732.78	10%	273.7	614.21	15% (92sq.ft)	20%
2732.78	15%	409.91	580.7	15% (87sq.ft)	15%
2732.78	20%	546.55	546.7	15% (82sq.ft)	20%

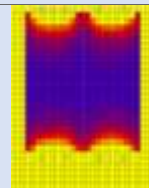
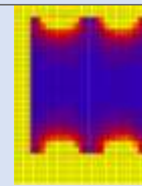
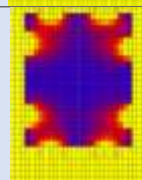
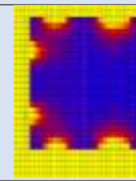
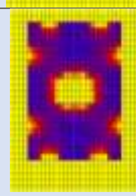
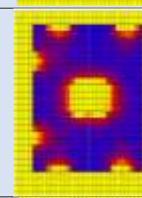
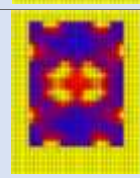
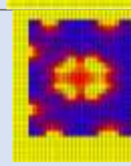
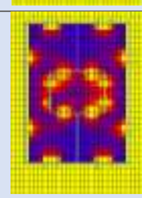
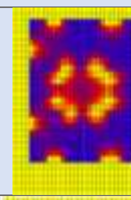
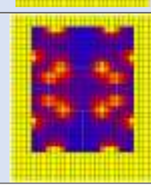
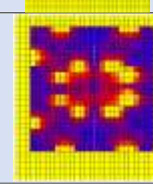
Table 26: Courtyard form results following LDA bye-laws

Permissible covered area Sq. Ft	Courtyard area in %age	Courtyard area in Sq. Ft	Zone area Sq. Ft	Glazing ratio %age	Special edition
3088.98	5%	154.4	733.63	15%	20%
3088.98	10%	308.89	695	20% with single window & one courtyard window 15% with two-sided windows & one courtyard glazing	20%
3088.98	15%	463.35	656.4	15%	20%
3088.98	20%	617.79	617.79	15%	20%

5.10 Comparison of Conventional vs Courtyard House

The (table 27) shows the simulation results carried out to compare conventional and courtyard house design.

Table 27: Daylighting comparison of courtyard Vs conventional house design

	WFR	DHA	LDA	WFR
Conventional with one window	20%			10%
Conventional with 2-sided window	15%			15%
Courtyard house with 5% courtyard of the permissible covered area	15%			15%
Courtyard house with 10% courtyard of the permissible covered area	15%			15%
Courtyard house with 15% courtyard of the permissible covered area	15%			15%
Courtyard house with 20% courtyard of the permissible covered area	15%			15%

6. Findings and discussion

In a conventional house design, if we provide one window, we need to keep the window-to-floor area ratio 15% in the case of LDA by-laws and 20% in the case of DHA by-laws to meet the recommended standard values.

If we provide two windows at different locations then to meet the optimum daylighting standards, we need to keep WFR 10% for LDA and 15% for DHA. By increasing the number of perimeter windows with the same window-to-floor area ratios better daylighting can be achieved. (Guthrie, 2003)

Increasing your courtyard area consequently decreases your zone area, as a result, the area of the window is also being reduced. With smaller windows, we are getting the same results. In the case of special cases where 70% of the glazing was allotted to the courtyard and 30% to the windows facing the setbacks, it was seen that we had to increase the size of the windows facing the setback to meet the standard requirements.

For 15% of the floor area ratio, it was observed that 50% glazing was found to be appropriate to achieve the standards, for the windows provided in the courtyard.

It was found that conventional house design incorporating bye-laws having more than one window in different locations proved to be equally sufficient than the provision of the courtyard (See Fig 8)

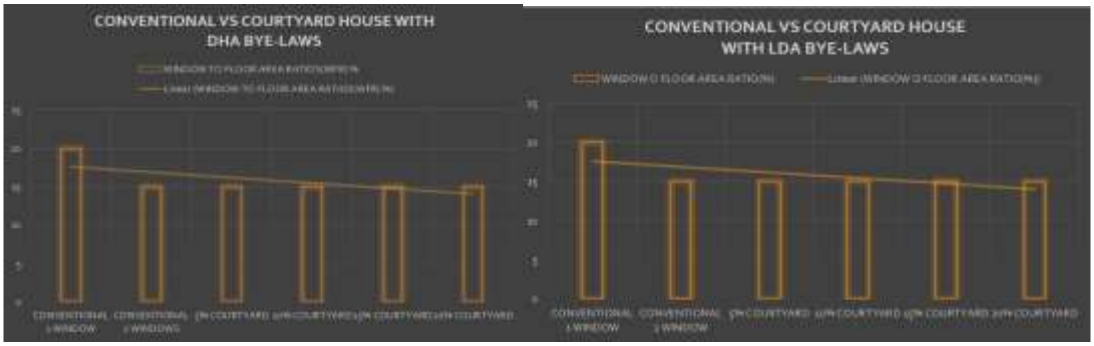


Figure 17: Comparison of conventional& courtyard houses with DHA & LDA Bye-laws

7. Limitations

- The limitation of the study was the utilization of only one method i.e., simulations. In this research, only the courtyard opening ratio was considered keeping all other factors constant which can be investigated for further research. Other parameters such as solar gain, energy consumption and thermal comfort are not considered in this research.
- Further research can be conducted on the effect of the depth of the courtyard on daylighting.
- The average daylight factor was calculated upon calculating the average daylight standards of the UK, USGBC, Japan, Dubai, and Malaysia. These six areas are selected on a random basis there are no fixed criteria for the selection.

8. Conclusions and Recommendations

This study highlighted the guidelines for the provision of windows according to the daylighting standards in a kanal house of Lahore. Moreover, it deduced results from the comparison of courtyard and conventional housing in Lahore. The key findings indicated that conventional house design incorporating bye-laws having more than one window on different locations proved to be equally sufficient than the provision of a courtyard. This study can be used in practice for appropriate daylighting and avoiding over-glazing. Moreover, can be used for the creation of Daylighting standards for Lahore. The study also highlighted that DHA bye-laws are much more measured to attain daylight than the LDA bye-laws.

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