

Energy savings by form design in schools

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ABSTRACT: This study is a part of a comprehensive study that aims to investigate the impact of school building form on energy consumption. The methodology included two parts: in part one the study conducted a survey that covered all schools under Abu Dhabi Department of Education and Knowledge (ADEK) authority; in addition to performing a design model analysis that helped identify the possible form design variables that can impact the building performance with their value ranges. Part two the study performed an hour-by-hour computer simulation to test the impact of different building form variables on energy consumption. The simulation was carried out in two phases, Phase I covered the investigation of the existing design models obtained from ADEK without any manipulation of the form variables. While Phase II covered a broader range of cases under more controlled conditions. The investigation was based on Abu Dhabi climatic conditions with respect to ADEK school requirements and Estidama green building guidelines. The simulation results revealed the effect of each design variable of the school building form on energy consumption and CO₂ emissions. The most important outcome of the study is the establishment of two concepts to evaluate the behavior of building form in influencing energy performance; i.e., form verticality and horizontality.

KEYWORDS: Energy consumption, school, building form

INTRODUCTION

United Arab Emirates (UAE) is located in the Middle East between 21.5° and 26.5°N and 51° and 56.25° with a total area of 77,700 square kilometers. The climate in the UAE can be classified as hot in summer, and warm to moderate in winter, the temperature can reach up to 50°C in July and August, which are considered as the hottest months of the year (Abdullah Al Mandoos, 2005). Due to the harsh climatic conditions of the UAE, building design with regards to improving thermal performance and reducing heat gains should be given a special consideration.

According to the Environmental Protection Agency (EPA), Americans spend 90% of their time in the indoor space. Regarding schools, statistics indicate that 84 million Americans, of which 73.7 million are children, spend almost their entire day at schools. Moreover, one out of five of these schools expressed dissatisfaction about indoor air quality (EPA, 2009). The inappropriate building designs cause an extensive reliance on mechanical and electrical systems, which leads to increase in cooling and heating loads and hence increase in energy consumption. In UK, schools are classified as the third most consuming energy buildings, while in USA schools consume 10.8% of the total electrical energy consumed by buildings (Pérez-Lombard, Ortiz, and Pout, 2008). Governmental and commercial buildings in Abu Dhabi are responsible of 9.3% and 48.2% of the consumed energy, respectively (Clarke, 2016). Between 2012 and 2015, the energy consumption of buildings in the Abu Dhabi increased by 33%.

Abu Dhabi Department of Education and Knowledge (ADEK) has launched the New School Model (NSM) in 2010; which is based on the Learning Community (LC) concept. The LCs known also as pods, families, academies, houses, and schools-within-a-school is a well-known concept that has been used for decades (Kellough and Jarolimek, 2008). Generally, the LC concept is based on dividing the school into subdivisions (learning communities) where each subdivision includes one or multiple grade levels. This is designed to provide intimate environments for both, students and teachers. Yet, each LC is designed with a certain degree of openness that reflects the level of integration intended for targeted students' grade level and

associated tasks (see Fig. 1). To facilitate the design process of schools and helps architects and engineers producing designs that satisfy ADEK's requirements, ADEK produced a design handbook and five architectural design models. One of the five models was created for the KG schools. There is also a plan to produce a new model (model 6) for very large schools; that has not released yet. The information in these resources include several sustainability features required by the green code of Abu Dhabi such as; the reliance on passive design strategies and the implementation of efficient electrical and mechanical systems. (ADEK, 2013). These models share the same finger-plan design but they differ in terms of their students' capacity and the educational cycles they accommodate. This paper belongs to a comprehensive research project that aims to optimize energy efficiency of the UAE schools through improvement of the architectural form design. It investigates the ADEK's design models.

The aim of the study is to investigate how energy consumption in school buildings responds to different designs of building forms. The current paper conducted a survey of school buildings and a design model analysis that helped to identify specific variables of the building form needed for optimizing the school buildings' energy performance; then it conducted hour-by-hour energy simulations divided in two different phases, Phase I aims to analyze and compare between the design models without controlling any variables. Phase II on the other hand examined produced models under controlled conditions.

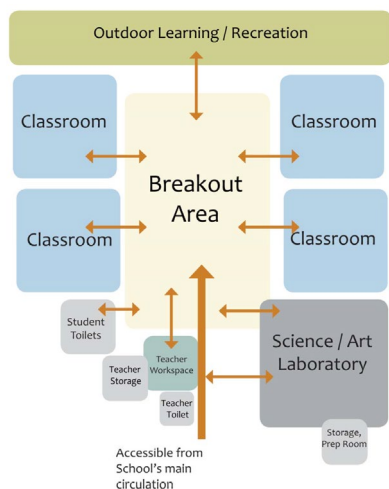


Figure 1. Learning Community Relationship diagram (ADEK, 2013)

1.0. LITERATURE REVIEW

Several previous studies tackled the relation between the building form and energy consumption (AlAnzi et al., 2009; Catalina, Virgone, and Iordache, 2011; Depecker, Menezo, Virgone, and Lepers, 2001; Koranteng and Abaitey, 2010; Ourghi, Al-Anzi, and Krarti, 2007). Al-Sallal (2016) has defined several considerations to help reduce the heat gain in buildings, these are the optimization of the building forms regarding its compactness and self-shading. Compacted forms which have less exposed areas to the climatic conditions are recommended in regions with hot dry climate as they prevent heat gains. Spread-out forms, on the other hand, are recommended in regions with hot humid climate. Moreover, building forms should be designed in a way that can maintain the passage of the cool breezes. Strategies to reduce energy consumption can be categorized into three main categories as follows (Al-Sallal, 2016; Kharecha, Kutscher, Hansen, and Mazria, 2010): (1) Strategies related to the planning and design, (2) Strategies related to the building envelope, equipment and material, (3) Strategies related to the added technologies. The building form, which is the focus of this study, is related to the first category. Several studies identified the most consuming energy systems in schools; generally, it was found that heating (for cold climates) and cooling (for hot climates) systems

consume more than 40% of the total energy consumed (DOE, 2013; Kim, Lee, and Hong, 2012). There are three (3) factors related to the building form that can have an impact on the energy consumption according to Al Anzi et al (2009). These are: the relative compactness (RC), the window to wall ratio (WWR), and the solar heat gain coefficient (SHGC). Due to the unlimited number of forms, the RC was used in many previous studies as an indicator of the building form. It was found in previous studies that the RC has a direct impact on energy consumption, the increase of the form RC leads to less exposed areas to the harsh climatic conditions, and hence, less energy is needed for heating or cooling (Pessenlehner and Mahdavi, 2003; Depecker et al., 2001). However, this method according to Pessenlehner and Mahdavi (2003), this method is not completely accurate for three (3) reasons; it does not count the self-shading, the transparent components, and the form direction. Yet these factors can have a significant impact on energy consumption.

2.0. METHODOLOGY

2.1. Survey of schools and design models analysis

In 2016, when this research started, there were around 411 schools in Abu Dhabi and Al-Ain regions including the old and new of the public and private schools. Public schools are designed based on design models generated by ADEK. ADEK advised to give priority for the new generation of public schools. Thus, public schools were considered in this study; in addition their typologies are more commonly used. There is a plenty of them; which can cause significant impact on the total energy consumption of schools. Moreover, old schools were no longer authorized by ADEK. Hence, the scope of this research is limited to the new generation of the public schools. The school design that had only KG level (Model 5) was not considered; as this type was considered as a special case; which can be investigated in a future study. The study started by surveying these schools in two mentioned regions. The aim of this survey was to investigate the total number of the new schools following each design model. The survey was carried out using several tools/resources: an online database application called School Finder, Google Maps, and School Contacts Excel sheet. The School Finder and School Contacts are databases available in ADEK website. The School Finder helped provide full information about all schools in Abu Dhabi Emirate, including their GPS coordinates. These coordinates were used in Google maps to view the site layout of each school. The School Contacts helped obtain other information such as school's types (public or private), gender, grades, and contacts. The survey tracked down a total number of 48 schools categorized by the four Design Models (see Fig. 2): 10 schools followed Model-1, 16 schools followed Model-2, 9 schools followed Model-3, and 13 schools followed Model-4.

The tracked down schools were analyzed to identify the design variables of the school form that have potential effect on energy consumption. The four models have finger-plan configuration (see Fig.3); with each finger includes a number of LCs distributed in 2-3 floors. The analysis also helped define the value range for each design variable (see Table 1).

2.2. Simulation

The computer simulation was performed using ENERWIN-e9 software. ENERWIN-e9 was based on an earlier version named EnerCalc. Both programs depend on hour-by-hour calculations and have been used extensively in previous researches (Degelman, 1999; Zhun et al. 2011;). ENERWIN-e9 has a great flexibility with regards to entering the design input data since it has a graphical method to enter the physical geometry of the forms and define the thermal zones in addition to allowing the change of input values manually. It is capable of simulating school buildings based on safe input data suggested by the program and allows the user select from three different standards (90.1-2010, 90.1-2007, or the Standard 189.1-2011 for Green Buildings); which considers the building type. The results generated by ENERWIN-e9 can serve the purpose of this research because it provides the utility energy/costs and a summary of the greenhouse emissions. It also provides thermal comfort analysis and peak HVAC loads. It provides weather data for over 4700 cities including the one for Abu Dhabi.

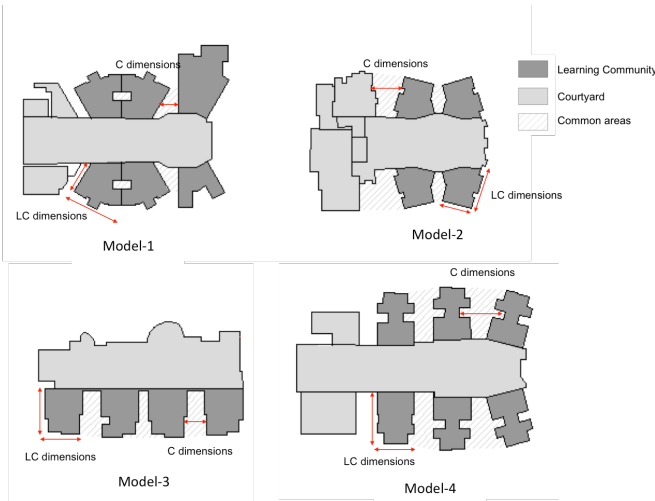


Figure 2: ADEK Design Models (ADEK, 2013)

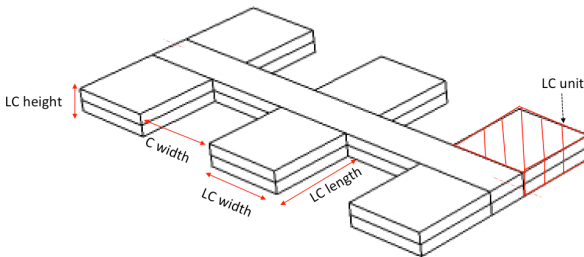


Figure 3: Representation showing the design variables of the finger-plan configuration of the school form.

Table 1. Design Model variables with their values.

Design Models	N° of Floors	Finger L×W (m); AR	Courtyard W (m)	WWR
Model-1	2	31×22.5; AR=1:1.38	0	40%
Model-2	2	33×22; AR=1:1.5	8	30%
Model-3	2	30×25; AR=1:1.2	12	30%
Model-4	3	38×27; AR=1:1.4	14	20%

2.2.1. Phase I

In Phase I, the aim was to investigate the four Design Models as they are practiced in real life (values for the investigated variables are kept as defined in Table 1) on energy consumption. In these models only the architectural configurations of the form differ from one model to another, while other variables such as the construction materials, equipment, occupancy schedules, are the same between the models. The design data of each model were derived from their drawings and entered into the simulation software ENERWIN-e9. These data included the following:

Data that are unique to each case:

The physical geometry of the building form such as the form outline, dimensions, and number of floors. This also included identifying the thermal zones.

The dimensions of the building components including the walls, roof, windows, and space height.

Total built-up area.

Common data between the cases:

Building orientation (E-W orientation was used in all models).
 The construction materials of the wall, roof, slabs' assemblies including the U values for each assembly. This also included the type of window glazing and shading.
 The electrical lighting system' power loads, type (Fluorescent), and cost. The target lux level was chosen as 500 lux in classrooms.
 The HVAC / AC type: VAV with parallel FCU (Central chilled water C.T.).
 Energy efficiency measures as prescribed by ASHRAE 90.1, 2010 version was considered.
 Occupancy schedules.

The aim of running the simulations was to detect any change in the energy consumption and environmental issues (CO₂ emissions) as a result of changing the variables of the building form.

2.2.2 Phase II

The previous phase tested the school design models of ADEK, as they are implemented in practice. This produced limitations in the obtained results due to the limited scope of the defined design variables. To overcome this limitation, Phase II was added. Phase II investigated the variables of the building form in a more controlled process (one variable was changed per a time). The cases in Phase II differed in variables that have effect on configuring the building form (i.e., finger dimensions/AR, courtyard width, number of floors, and WWR); while other variables were fixed (Table 2). Phase II included 16 cases (see Fig. 4), planned based on a multiplication of the following:

- 2 alternatives for the LC fingers' configuration (LC-1= 20*37.5 with AR= 1:1.875 and LC-2= 27.38*27.38 with AR= 1:1).
- 2 alternatives for the C width configuration (C-10m and C-30m).
- 2 alternatives for the number of floors (2 floors or 3 floors).
- 2 alternatives for the WWRs (20% or 40%).

3 FLR	2 FLR	WWR 20/40%	
		C-10	LC-1 20*37.5m AR= 1:1.875
		C-30	
		C-10	LC-2 27.38*27.38m AR= 1:1
		C-30	

Figure 4. Phase II cases.

3.0. RESULTS AND DISCUSSION

The results of the energy simulation for the four models, expressed in in MJ per square meter per year, are shown in Figure 5. Model-1, proved to consume more energy than the other models. Model-4, Model-3, and Model-2 achieved 37%, 4%, and 3% energy savings respectively, compared to Model-1. The major difference in the design of form between the four models was the building height and WWR; Model-4 has three floors with 20% WWR and larger courtyard spacing while the other Models have 2 floors with either 30% or 40% WWR and smaller courtyard spacing. The other design variables between the tested cases are either the same (such as the orientation, the building envelop construction materials) or very similar (such as the courtyard size and the LC size). When comparing the energy consumption of Model-1, Model-2, and Model-3, one can find that they have similar results although they differ

in their WWR values (Model-1 has 40% WWR while Model-2 and Model-3 have 30% WWR). Since Model-4 achieved the best energy savings, this indicates that increasing the form height (in terms of number of floors) has a major effect in reducing energy consumption. That is because taller buildings result in more compact forms. Actually, Model-4 could have achieved even better savings if it had smaller courtyard spacing. The CO₂ emissions results showed a consistent pattern with the energy consumption results (see Fig. 6).

Table 2. Constant variables among the cases with their values, Phase II.

Constant Variables	Value
Floor Area	12,630 m ²
Form Axis Direction	North-South
Glass U-Factor	6.814 Watt/m ² . C
Wall U-Factor	0.505 Watt/m ² . C
Roof U-Factor	0.358 Watt/m ² . C
Occupancy densities	Based on ASHRAE 90.1 2010 standards
Electrical lighting power densities	10.7 W/ m ² Based on ASHRAE 90.1 2010
Ventilation rates:	CS1.829 L/s/ m ² Based on ASHRAE 62.1 standards
Ceiling height:	3.75m
HVAC system	VAV w/ parallel FCU (Cent. Chilled Water C.T.)
Electrical lighting system	Fluorescent tubular 100 Lum/watt
Exterior Exposure	Grass
Target lux in classrooms	500 Lux

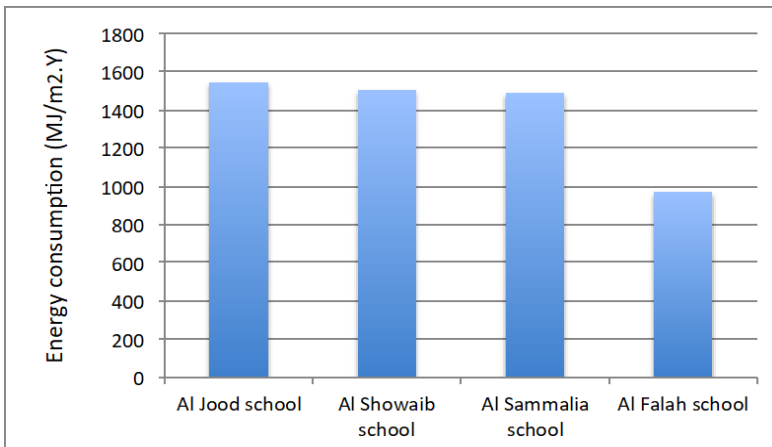


Figure 5. Energy consumption results, Phase I.

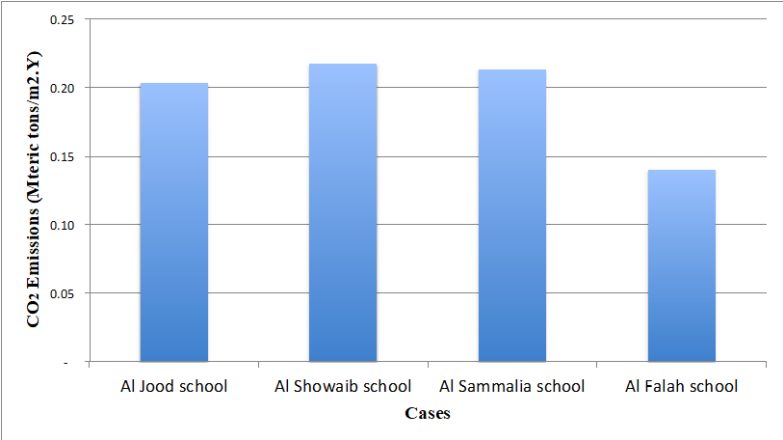


Figure 6. CO₂ results, Phase I.

The results of energy simulation in Phase II demonstrated a similar pattern with regards to the impact of building height (number of floors) on energy consumption. A reduction that is equal to 30% of the total consumed energy was attributed to the cases with 3 floors compared to the corresponding cases with 2 floors. Regarding the finger configuration, it can be seen from the results in Figure 7 that in the cases with 2 floors LC1 (the most linear form with AR = 1:1.875) consumes more energy compared to LC2 (the squared form with AR = 1:1), the increase can reach up to 8% of the total consumed energy. However, this pattern was not consistent in the cases with 3 floors. The impact of the WWR is also remarkable, a reduction of 5% of the total consumed energy achieved when WWR decreased from 40% to 20%. Regarding the courtyard configuration, it can be seen that no significant impact was achieved between the cases that differ in their courtyard width values. The CO₂ emission results showed a consistent pattern with the energy consumption results (see Fig. 8).

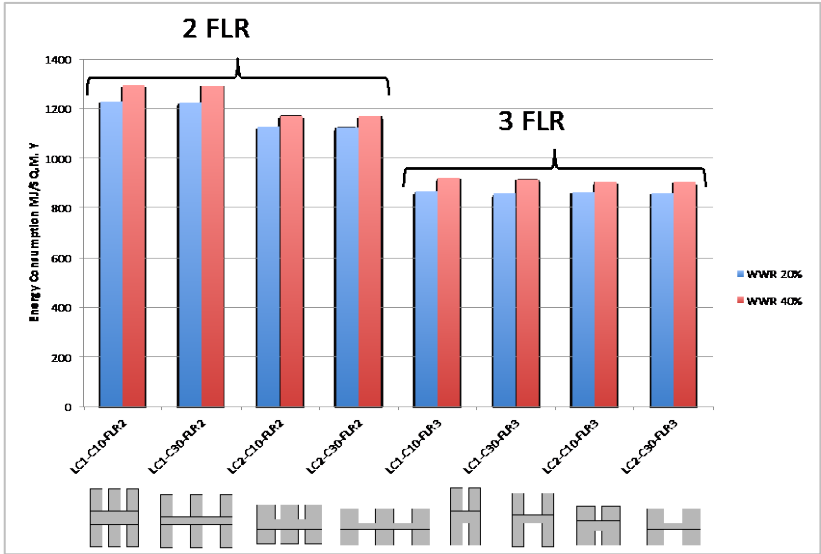


Figure 7. Energy consumption results, Phase II.

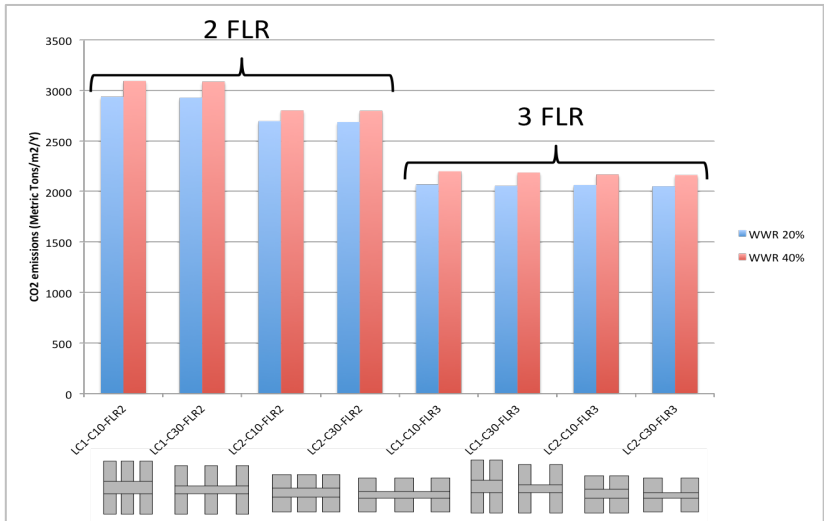


Figure 8. CO₂ emission results, Phase II

The savings achieved by the more compact building form confirms the findings of previous research (Pessenlehner and Mahdavi, 2003; Depecker et al., 2001; AlAnzi et al., 2009). To understand this phenomenon better, two form design variables were established. These are the verticality and horizontality of the form. The two terms can be expressed as:

Form Verticality = Vertical Surface Area / Vertical+ Horizontal Surface Area

Form Horizontality = Horizontal Surface Area / Vertical+ Horizontal Surface Area

These two variables were calculated for the tested cases in Phase I and Phase II and presented in Figures 9-12. One can observe that when increasing the verticality of the form, which corresponds to reducing the horizontality of the form, energy consumption decreases. This can be justified by the amount of solar gain transferred through the building surfaces. Both Abu Dhabi and Al-Ain are located very near to the tropic of cancer where the summer solar radiation is perpendicular on the roof surfaces. Hence, forms with high ratio of horizontality (or less ratio of verticality) are more exposed to this effect, and therefore, higher cooling loads are required.

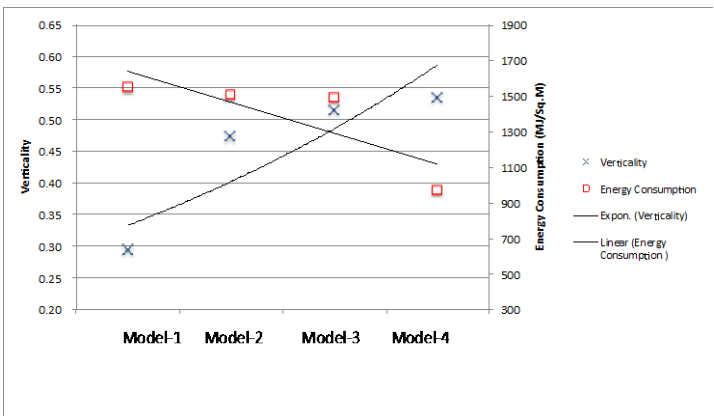


Figure 9. Phase I, the correlation between verticality and energy consumption

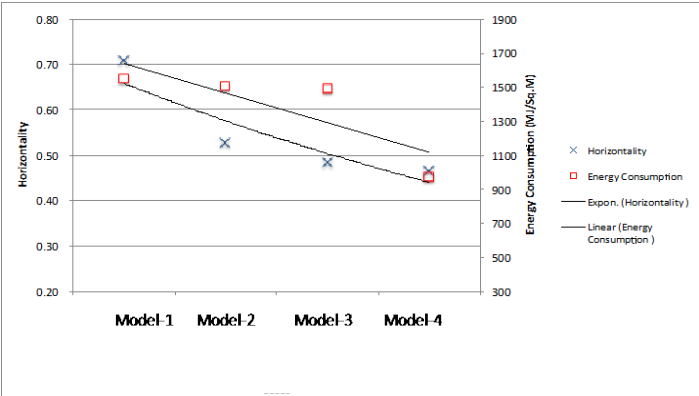


Figure 10. Phase I, the correlation between horizontality and energy consumption

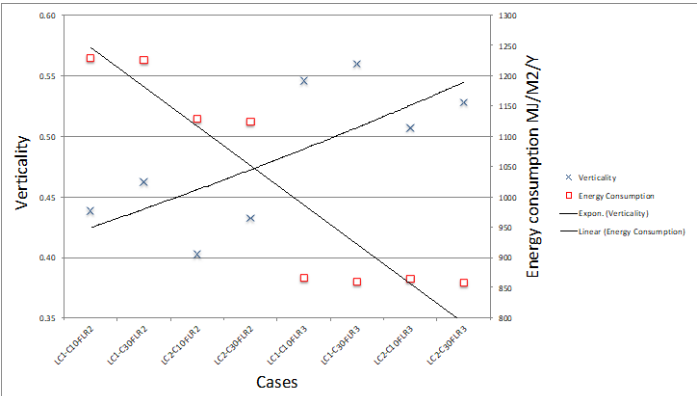


Figure 11. Phase II, the correlation between verticality and energy consumption (WWR20%)

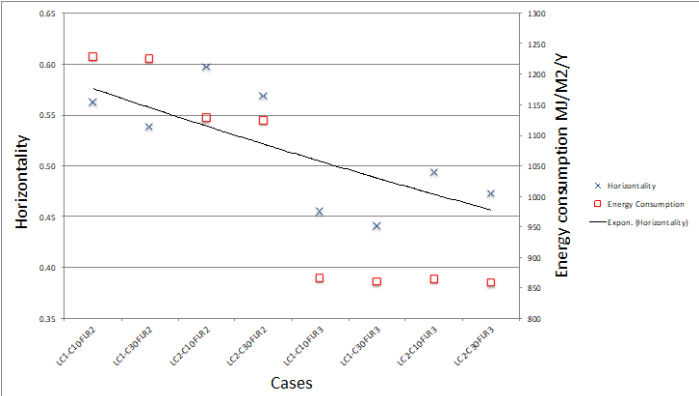


Figure 12. Phase II, the correlation between horizontality and energy consumption (WWR20%)

CONCLUSIONS

The design model analysis helped address a number of design variables that represent the building form based on the finger-plan configuration and have influence on energy performance in school buildings. These variables are: the size and AR of the fingers that include the learning communities, the width of the courtyard, the number of floors (height), the form axis direction (orientation) and finally the WWR. The design models analysis helped also define the value ranges of the investigated variables. The most important finding based on the

conducted energy simulation of the cases from Phases I and II was the effect of the form verticality on energy savings (30% energy savings when the number of floors increased from 2 to 3, keeping the same total floor area). The WWR had also potential for improvement of energy savings; yet it was not as significant as the form verticality (5% energy savings when WWR was decreased from 40% to 20%). This paper depended on testing 20 cases only. To have a comprehensive investigation of the effect of school form, especially with the significant design variable established here (i.e., the form's verticality as opposed to its horizontality), future research is needed. The paper covered only limited number of configurations of the finger-plan design considering the most dominant building orientation (E-W form-axis direction) as dictated by the direction of most streets in Abu Dhabi and Al-Ain cities. Future research should cover larger number of configurations of the finger-plan design typology. It should also include other design configurations such as the courtyard, the rectangular/square, the circular, and other configurations. Other design variables that can be covered in future research are the effect of landscape/greenery, green roofs, shading devices, advanced glass technologies, and potential of passive cooling systems.

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