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Architectural design optimization of school buildings for reduction of energy demand in hot and dry climates of Iran

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Abstract

School buildings, which form a major part of public buildings, are considered to be one of the maximum consumers of energy in Iran. Based on building typology and occupancy patterns, school buildings have a significant potentiality for energy optimization while providing thermal comfort. This study investigates the architectural design parameters such as orientation, optimum window-to-wall ratio, space organization, sun shading, and building shape, which have a considerable impact on the energy demand. For the purpose of this study, a typical elementary school is selected, modeled, and analyzed by integrating different design measures using a dynamic simulation software tool. The optimum values for various architectural design parameters are calculated. The results reveal that through energy efficient architectural design, the primary energy demand of the studied case has reduced by 31% while maintaining visual and thermal comfort as compared to the existing building.

Keywords: *Energy consumption, Energy efficient architecture, School, Thermal comfort, Building envelope.*

1. Introduction

The architectural design of buildings has a significant impact on the consumption of non-renewable resources. In developed countries, the energy consumption in the building sector is more than 33% of the total energy consumed. In Iran, this number has increased to more than 40.6% [1]. Not only are the residential and commercial sectors the main consumers of energy in Iran, the energy consumption in public buildings in this country is also high in comparison to the universal standards.

The average energy consumption in school buildings in Iran, as a major category of public buildings, is more than 160 kWh/m^2 [2], which is 2.5 times more than the energy consumed in high-performance schools in developed countries, which is approximately 65 kWh/m^2 [3].

Despite the high energy consumption, thermal comfort is not usually provided in classrooms [4]. Recently, various programs such as Smart Schools in the United States of America and The Schools for the Future program in Europe have attempted to provide high-performance learning environments by sustainable site planning and landscaping, good building envelope design, appropriate lighting, and an increased use of daylighting in order to improve student performance and increase comfort levels [5].

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Not only do energy-efficient schools reduce the energy use and cost but they also increase thermal and visual comfort and space quality and help preserve non-renewable energy recourses. Taking into consideration the different parameters affecting the school's energy demand, previous studies can be categorized into three main groups. First, the studies that consider the optimization of mechanical and electrical utilization of schools [6-8]; second, the ones that study the architectural design and constructional parameters such as shadings and thermal insulation [9-12]; and third, the studies that consider energy management factors in schools [13-16].

In Iran, the Energy Efficiency Organization's actions for reducing energy consumption in schools are mainly divided into two categories: 1. Reduction of energy use through construction details in new buildings, which is mainly realized by the installation of double-glazed windows and the thermal insulation of the building envelope, and 2. energy management in the existing buildings [17]. However, the organization has failed to consider the impact of architectural design on the reduction of energy consumption. The State Iranian Organization of Schools (renovation and development), which is responsible for designing K-12 schools, has proposed a climate zoning for educational buildings and provided specific design guidelines for designing schools to withstand the cold climate of Iran [18]. There have been no particular regulations and guidelines for an energy-efficient design of school buildings in the hot and dry climate although the total energy consumption of schools in this climate is 41.91% of the total energy consumed by school buildings across the country [19].

With the aim to investigate architectural energy-saving strategies in order to minimize the heating, cooling, and lighting energy demand in school buildings in the hot and dry climate of Iran, a typical existing twelve-class elementary school building in Shiraz (29°37′N 52°32′E) has been selected as a base case for analyzing and assessing architectural energy-conservation strategies. According to the Shiraz psychometric chart (Fig. 1), thermally comfortable hours can be increased to 46% in buildings by using passive design strategies. The energy performances are analyzed using the dynamic simulation software tool DesignBuilder [20], which is the first comprehensive user interface for the EnergyPlus dynamic thermal simulation engine. Hourly Weather Data of Shiraz that are based on daily records from 30 to 43 years are used as the weather data for simulations.

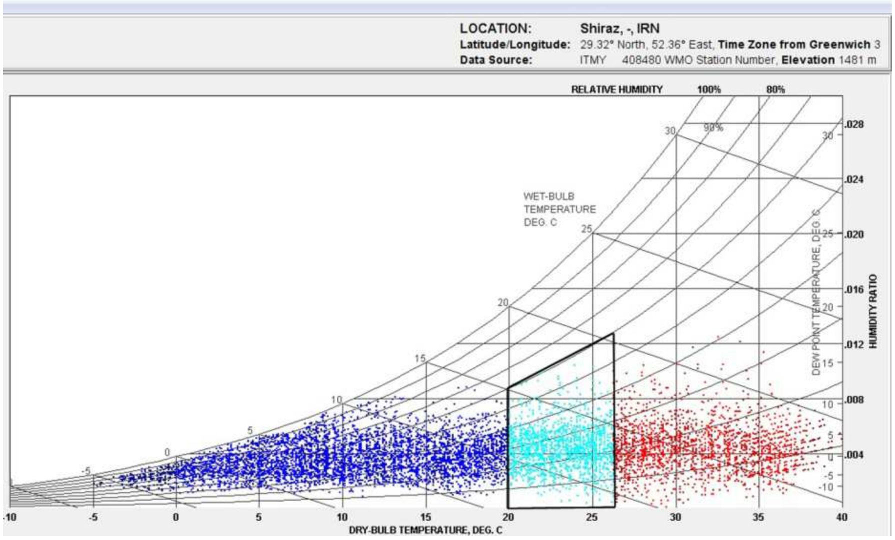

Fig. 1. ASHRAE Shiraz psychometric chart [21]

2. Methodology of Research

One of the most cost effective and ecological methods of energy saving in buildings is the reduction of energy requirements through climate responsive architecture. Due to the fact that energy saving through the optimization of architecture is not only cost-neutral, resource-efficient and carbon-neutral but also has a very high energy-saving potential, the first and most important strategy to save energy should be an optimized and climate responsive design. Architectural Energy Efficiency is a parametric method of energy saving which separately studies the effects of various energy-related architectural factors on the energy demands of buildings. Dynamic energy simulation methods are used to find the optimum value for each of the architectural factors [22]. In this studyin order to find the optimum value for different architectural strategies the existing school building has been modeled and the energy consumption for heating, cooling and lighting has been calculated by dynamic energy simulation. Although this study aims to investigate the effect of architectural strategies on the energy demand of school buildings, two construction parameters are analyzed at the first stage of the study; 1. The thermal insulation of the building envelope since is the only energy conserving action in process in Iranian school buildings and 2. Infiltration since has an important impact on the energy demand. Then various architectural parameters based on their importance and effects on the energy demand are analyzed respectively in order to define the optimum value for each parameter. The optimum value of every parameter is assigned to the model then the next parameter is analyzed and its optimum value is calculated through various simulations. The lighting, heating, cooling and the primary energy demand is calculated in each simulation. The primary energy [1] demand since considers the energy balance is used to determine the optimum value of the parameters in the simulations.

2.1. Base case school building characteristics

The base building is a three story prototype school building which has a total ground floor area of 1380 m^2 (fig.2 and fig.3). The building envelope is uninsulated with single-glazed [2] and metal framed windows. The U-Values of the thermal envelope components are presented in table 1. The building uses a HVAC system [3] for heating and cooling. The energy sources used for space heating and cooling are natural gas and electricity. The heating and cooling set points are fixed to 21°C and 26°C to provide thermal comfort in indoor areas. The lighting level in classrooms is set to 300 Lux due to the School Renovation & Development Organization regulations [23]. The maximum allowable discomfort Glare of 20 is considered due to regulations in classrooms[24].There are thirty five students in each classroom and the building is occupied from 7 am to 2 pm Saturday to Thursday, from September 21 to June 21 except official holidays. The occupancy pattern, students clothing index and metabolic rate, which are applied for simulations, are based on a real primary school condition in the studied context.

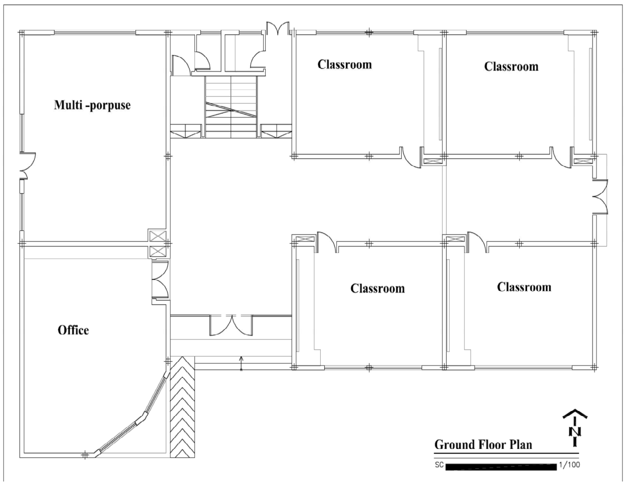

Fig. 2. Ground floor plan of the base case school

Fig. 3. South view of the base case school [26]

3. School Building Energy Optimization Design

The selected case was modeled and analyzed by integrating different design strategies into 143 different models using the dynamic simulation software tool. The results obtained from various simulations are reviewed and discussed in each section. Although the aim of this study is to investigate architectural energy saving strategies, thermal insulation and infiltration as two important construction factors affecting the energy demand in buildings are studied in the first stage of the analysis. Various design variables investigated in this study are summarized in table 1.

Table 1 Design variables investigated in order to define optimum values

Design Variable			Simulation Range	Base Case	Recommended Value
Constructional Parameters	Thermal Insulation (w/m^{2}k)	Wall	0.82 & 1.34	0.82	0.82
		Ground floor	0.76 & 1.95	0.76	0.76
		External floor	0.67	0.67	0.67
		Roof	1.59 & 0.8	1.59	0.8
		window	5.77 & 4.26	5.77	4.26
	Infiltration (ach)		0-4ach	2 ach	0.75ach
Architectural Parameters	Window/wall	South	0-100%	40%	20%
		North	0-20%	30%	15%
		East &West	0-15%	0%	5%
	Shading	South	0-1.6m overhang	0	0.6m
		North	0-1m side fin	0	0.6m
		East& West	0-1m crate shading	0	0.5m
	Orientation		0°-360°	0°	0°
	Class Arrangement		One side north class One side south class Two side class	Two side class	One side north class
	Formal Parameters	Elongation & Compactness (length/width)	1-3	1.5	2
		Building Stories	1-3	3	3
		Plan Shape	Linear shape L right shape L left shape H shape U south shape U north shape	L left shape	Linear shape U south shape
		Roof Form	Flat roof North sloped roof South sloped roof Gable roof Barrel roof	Flat roof	North sloped roof
		Roof Slope	0-30°	0°	10°
		Wall Slope	0-30°	0°	20°
		Ground Level Adjacency	(+0.5)-(-1.5)	+0.5m	-1.5m

3.1. Construction Parameters

3.1.1. Thermal insulation

Since school buildings have specific occupancy patterns, certain regulations should be considered for the thermal insulation of these buildings. In Iran the ministry of energy has not developed specific regulations for the thermal insulation of school buildings and they are considered the same as restaurants and hospitals. In order to investigate the effectiveness of the building envelope U-values given by the Iranian ministry of energy [27], they are considered in the base school model and the energy demand is calculated and compared to the building with the existing U-values. According to the regulations only the roof and windows should be insulated and the other building components have an appropriate U-value. Results of the simulations are shown in Fig.4. and Fig.5. According to the results by using thermal insulation in the roof and double glazed aluminium windows the primary energy demand of the school building decreases 6% in comparison to the existing case. This is due to the reduction in the heating energy demand and results have shown that insulation does not have a tangible effect on the school cooling demand which is because of the high number of students in the classrooms. The recommended U-values are included in the base case for next analyses.

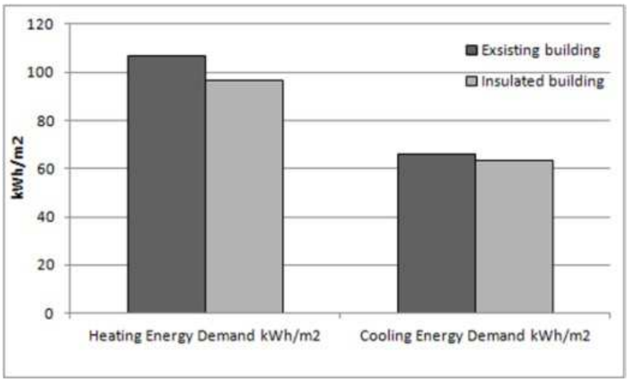

Fig. 4. Comparison of the heating and cooling energy demand of the existing and insulated school

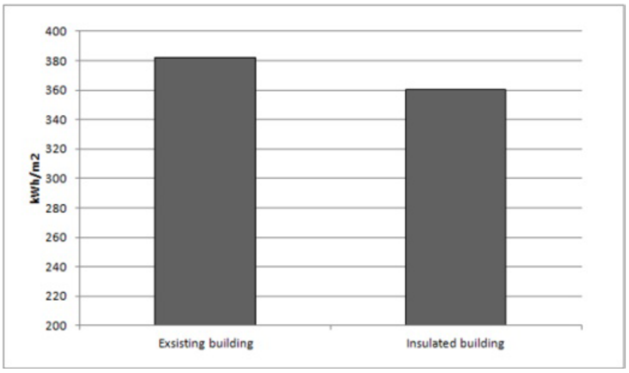

Fig. 5. Comparison of the primary energy demand of the existing and insulated school building

3.1.2. Infiltration

Infiltration is one of the important construction parameters that affects the energy demand in buildings and is determined by airchange per hour. Air tightness of the building envelope relates to the window and door type, materials used and the quality of the construction process [28]. In Iran no regulations have been developed for the air tightness of buildings and since the low construction quality of buildings, infiltration has been considered as one of the main routs of heat loss in buildings. Air tightening the building envelope will reduce the heat lost and improve the indoor air quality. The base case has been modeled including different air change rates. The results have been shown in Fig.6. Simulations show that an infiltration rate more than 0.75 ach increases the primary energy demand in comparison to the existing case. Since the high density in classrooms, decreasing the air change rate can affect the indoor air quality due to the lack of fresh air. Specific studies must be done in order to determine the appropriate amount of air change in classrooms in Iranian schools. Increasing the airchange rate in school buildings in this climate will increase the heating energy demand while it decreases the cooling energy demand, because it causes a heat transfer from the inside to the outside. The airchange moves the collected heat from internal and external gains to the outside and acts as natural ventilation. But if school buildings are occupied during the summer, in which the outside air temperature is much higher than the comfort zone, after a specific amount of airchange rate, the cooling energy demand will increase too. In this study 0.75 ach is calculated as the optimum infiltration rate and is assigned to the model. Previous studies done in school buildings [12, 29] have also obtained the same result. It is clear that an air change rate of 0.75 per hour is not appropriate for schools. According to ASHRAE 62.1[30] in classrooms, a level of approximately 4 to 5.5 air change rates per hour should be provided during occupancy. This should be achieved by considering both air tightening the windows and envelopes and by controlled ventilation which was considered in the simulations. The primary energy demand of the model with 0.75 ach infiltration decreases 11% in comparison to the base case which has an infiltration rate of 2 ach.

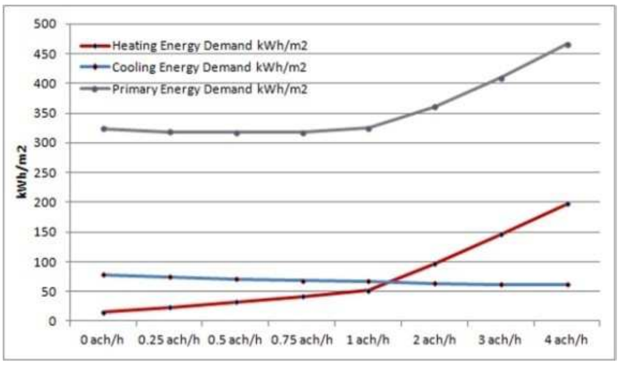

Fig. 6. The impact of airchange rates on the heating, cooling and primary energy demand in the studied school building

3.2. Architectural Parameters

3.2.1. Window-to-Wall Ratio

The Window area in different orientations is one of the most important architectural factors affecting the building's energy demand. Windows provide solar heat gain, daylight and even natural ventilation for indoor spaces. Since windows are the weakest thermal link in the building envelope, their design has a direct impact on the thermal comfort and the energy demand in buildings. In school buildings due to the room size, the window-to-wall ratio is usually high. By designing appropriate windows a balance between lighting, heating, cooling and ventilation would be obtained. The existing model has a window-to-wall ratio of 40% in south and 30% in north and 2% in east and west sides. In order to define the optimum window-to-wall ratio in different sides of the building several simulation are done. First the optimum window-to-wall ratio for the south walls, second for the north and third for the east and west walls is calculated. An important parameter considered in defining the optimum window-to-wall ratio is the daylight factor that should not descend 2% in classrooms [31]. Results indicate that 10% window-to-wall ratio in all directions would be optimum based on primary energy demand (fig.7). Since this window-to-wall ratio would not provide the minimum daylight factor required for school areas, 20% window was considered as the optimum for all directions in the first stage and then more simulation including 20% window in south facade and different ratios in other direction are done in order to find the optimum amount in other directions. According to the results the lighting energy demand decreases by increasing the window/wall ration from 0% to 100%. This reduction is high from 0% to 20% but after 20% the reduction is very slow especially after 30% it can be connived. In the viewpoint of energy efficiency this means that 20% window/wall ratio is optimum when only lighting is considered. Also the heating demand first increases by increasing the window/wall ration from 0% to 10% and then decreases with a high inclination due to the increasing amount of solar gain. This shows the high potentiality of using solar gains for heating buildings in the studied context Despite the high potentiality of solar gain for heating, the cooling energy demand highly increases by increasing the window/wall ration. Results show that the building with optimum window to wall ratio has 8% less primary energy demand in comparisons to existing building (fig.8). Due to the results the appropriate window to wall ratio for the south walls is 20% and 15% for the north and 5% for the east and west walls. The determined window-to -wall ratios is assigned to the model and the new model is used for the next analysis.

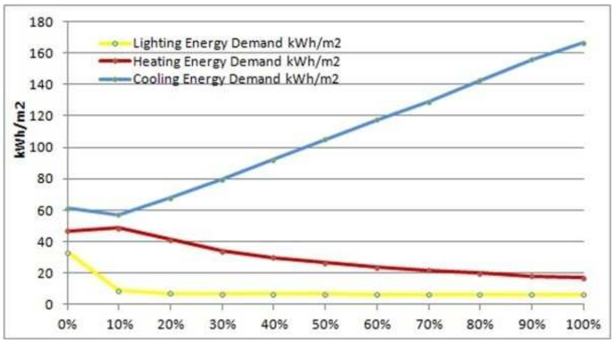

Fig. 7. The lighting, cooling and heating energy demand of the school building with different window/wall ratios

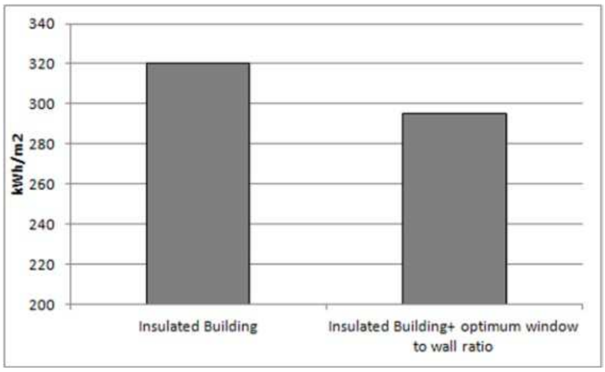

Fig. 8. Comparison of the primary energy demand in the existing model and the one with optimum window/wall ratio

3.2.2. Sun Shading

Sun penetration in indoor spaces is the main reason for space overheating in warm seasons. In order to provide appropriate daylight level in classrooms windows are relatively large and shading these windows to prevent sun penetration in warm months is critical. Sun shading is an effective strategy in decreasing cooling energy demand in hot and dry climates. The base case school has no shading in all directions. The appropriate sun shadings for the south, north, east and west windows have been determined through simulation and analysis. Due to the sun angle, overhangs and side fins are used as effective shadings in the south and north that can control the sun penetration in winter and summer. Results show that increasing the overhang projection size increases the heating and lighting energy demand and decreases the cooling energy demand. The increase in heating energy demand is more than the decrease of cooling energy demand which is because of the high solar altitude in the studied context and the school occupied hours which is mostly in the morning. A balance between the lighting, heating and cooling energy demand can be obtained by considering appropriate shadings which can allow sun penetration in cold months and prevent it in warm months. Results show that the optimum shading for south facing windows is 0.6 meter width overhangs with 0.2 meter vertical offset from the top of the window, 0.6 meter width side fins for the north facing windows and 0.5m crate shading for east and west windows (fig.9). Result show that the primary energy demand of the building with considering the recommended shading devices decreased 5% in comparison to the last model (fig.10). The Iranian state organization of schools does not usually build external shadings in school building projects due to construction regulations and uses internal shadings (blinds). Simulations show that internal shading strategies do not improve the energy demand in school buildings in hot and dry climates. Since external sun shadings have a lower impact on energy demand in comparison to window to wall ratio, due to its significant impact on the cooling energy demand it should be taken into consideration

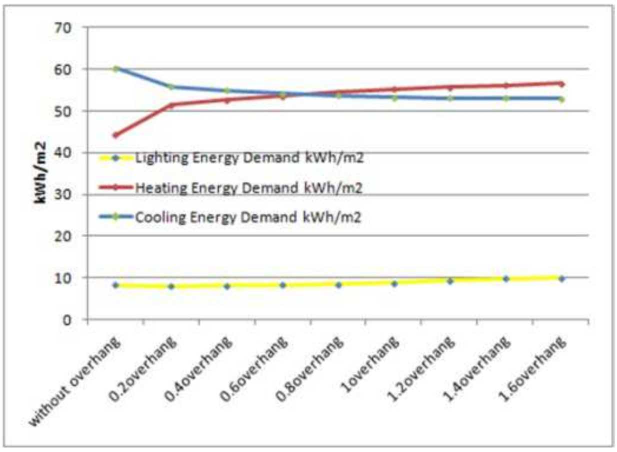

Fig. 9. The lighting, heating and cooling energy demand of the school building by increasing projection size of the overhang

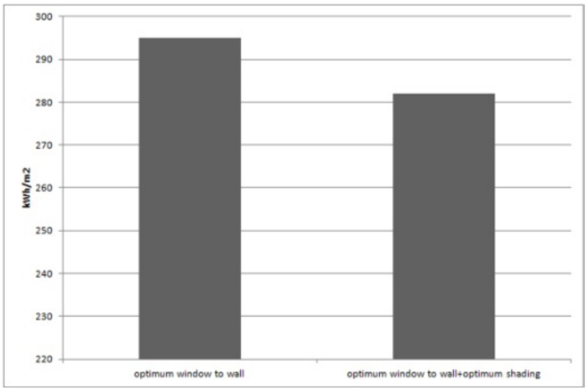

Fig. 10. Comparison of the primary energy demand of the school building with and without external shadings

3.2.3. Building orientation

Building orientation is an important architectural factor in the building energy consumption. The effect of this parameter on the lighting, heating, cooling and primary energy demand of the base case school building is investigated by simulating the building in different orientations. By optimizing the school building orientation the sun radiation and daylight can increase in summer and winter and the energy demand for lighting, heating and cooling can decrease. The school building's orientation and the energy demand are directly linked due to the window orientations. The sun radiation that surfaces receive in summer and winter relates to the building's orientation and the altitude of the context. The dominant wind direction is also considered in defining the optimum orientation. Results indicate that the most appropriate orientation for the studied case is the existing condition which the building is oriented to south and elongated to east and west. The behaviour of the lighting, heating, cooling and primary energy demand of the school building is shown in Fig. 11.

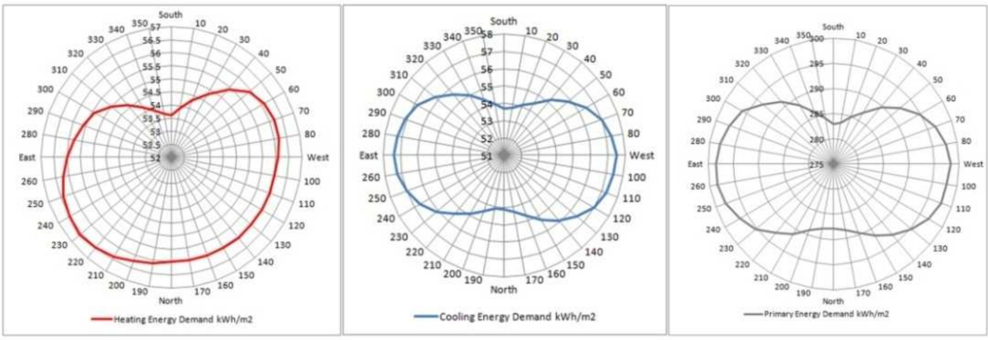

Fig. 11. The heating, cooling and primary energy demand of the school building in different directions

3.2.4. Class Arrangement

Room arrangements should be based on the heating and lighting and cooling demands of the space. Class arrangement in school design is a major consideration. Classrooms build on both sides of the building and classrooms on only one side can cause different design challenges. Simulations were done in order to define the optimum classroom arrangement in the context of the study. In this study three kinds of class arrangements are modeled and compared to each other: 1. base case (two side classrooms on the north and south) 2. one side north classrooms 3. one side south classrooms. Results show that the one side north classroom arrangement has the minimum energy demand among other arrangements (fig.12). One side north class arrangement decreases the lighting and heating energy demand in comparison to the two side arrangement because of the daylight and the solar gain of corridors. Although this reduction is low, this arrangement is recommended. Since classrooms are on the north side so they benefit from appropriate daylighting for learning and also the corridors which are on the south side act as solar spaces in cold months and in warm months by opening the corridors and classes' windows cross ventilation can help cooling the school spaces.

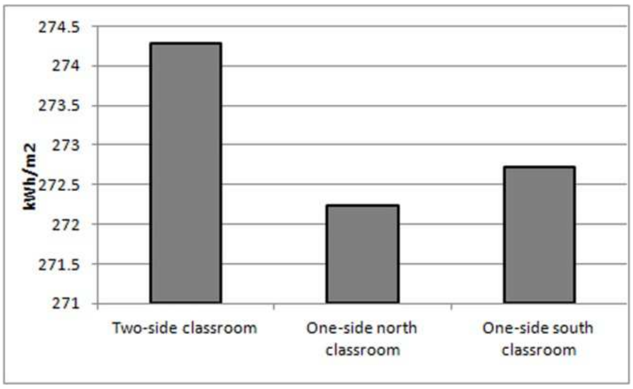

Fig. 12. Comparison of the primary energy demand in the school building with different class arrangements

3.2.5. Architectural Form Analysis

The energy demand of buildings specifically depends on the shape and typology of the building. Form and shape are critical factors in absorbing and radiating heat during the day and night and thus a critical parameter in the building's heating and cooling energy demand. Various formal factors including elongation and compactness, number of stories, plan shape, roof form, wall slope and the ground adjacency level are investigated in order to find the optimum value for each parameter. The simulations have been done in 6 steps and the optimum value for each measure has been assigned to the model and used for the next analysis. The base school building is a three story L shape building with a projection on the left side and the building ground floor is 0.5 m above the ground level. The model used for formal simulations has thermal insulation according to regulations, optimum infiltration rate, and window to wall ratio, sun shadings, orientation and class arrangement. Formal parameters investigated in this study and the recommended values are shown in table1. Results are shown in Fig. 13, Fig. 14, Fig.15, Fig.16 and Fig.17.

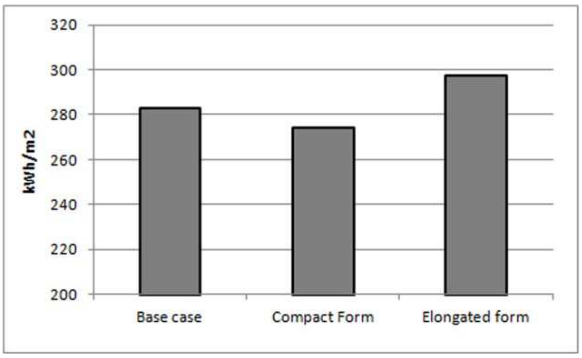

Fig. 13. The effect of form compactness on the primary energy demand in the school building model

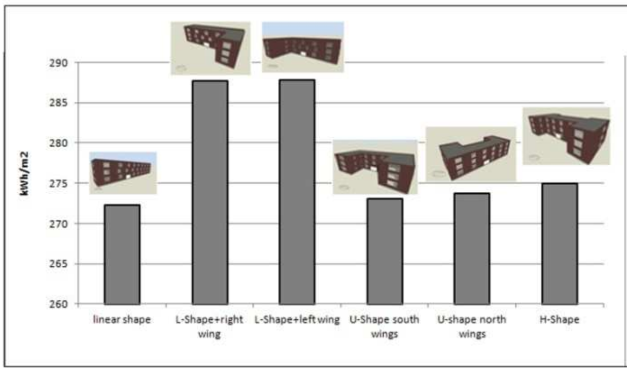

Fig. 14. The Primary energy demand of the school building with different plan shapes

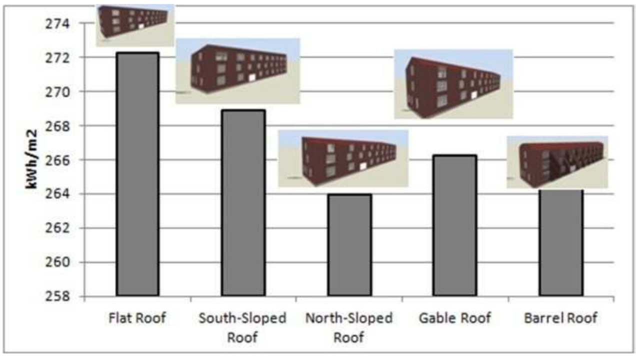

Fig. 15. Comparison of the school building primary energy demand with different roof forms

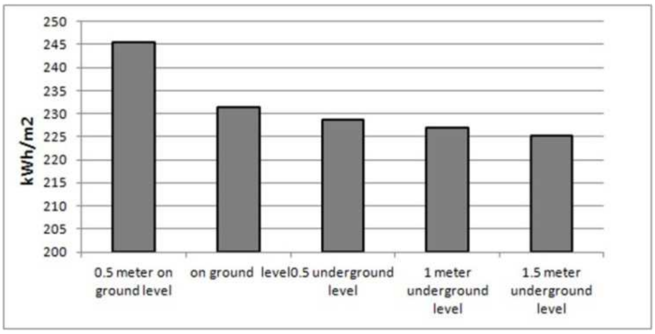

Fig. 16. The effect of ground adjacency level on the school building primary energy demand

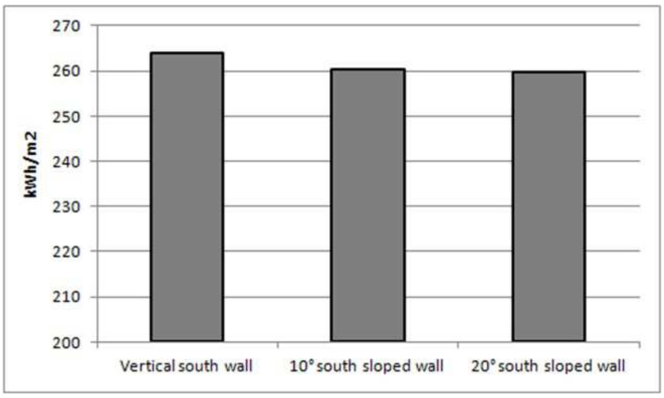

Fig. 17. The effect of south wall slope on the primary energy demand

4. Prioritizing Energy Saving Strategies in School Buildings

In this study various simulations have been done in order to define the architectural strategies that have a significant effect on the energy demand in the studied base case school building. It should be noticed that the results of primary analyses such as thermal insulation and infiltration, window/wall ratio, sun shading, orientation could be used for school buildings in the studied context since the climate and occupancy patterns are similar. But in order to define the optimum values for the formal strategies simulations should be done in each case. Some strategies studied in this case had a more significant impact on the primary energy demand in comparison to others. The effectiveness of the studied constructional and architectural strategies is categorized into four groups. The effect of different groups of strategies on the primary energy demand decreases from group one to four.

Group one: optimum infiltration rate, optimum window-to -wall ratio and optimum ground adjacency level of the building surfaces have the highest effect on decreasing the primary energy demand of the studied school building. 20% opening on the south facing, 15% openings on the north facing and 5% opening in the east and west side of the building reduces the primary energy demand 8% in comparison to the existing building. Also by burying the school building 1.5m in the ground the primary energy demand increases 8% in comparison to the building under the same condition that is built on a 0.5 concrete base. Results show that by increasing the ground adjacency level from 0.5 meter over the ground to 1 meter underground the heating energy demand first decreases and from more than 1 meter it starts to increase that is due to the humidity increase in cold months (fig.16). The cooling energy demand decreases by increasing the ground adjacency level because of the low mean ground temperature in warm months in comparison to the outside air temperature. Results show that by burying the building in the ground the primary energy demand is reduced 8% in comparison to previous model. This architectural strategy is common in traditional historical buildings in the studied context.

Group two: Thermal insulation of the building envelope and using sloped south walls are the next priority in decreasing primary energy demand in the school building. In Iran the ministry of energy has no specific regulation for thermal insulation in school buildings. Results have shown that the existing regulations do not have a specific impact on the energy demand in the studied case and reduce the primary energy demand only 6% in comparison to the existing building that has no thermal insulation. This reduction is due to the reduction in heating energy demand and thermal insulation does not have a tangible effect on cooling energy demand in the studied case. It is concluded that the existing thermal insulation regulations should be revised by considering the context climate data and the building occupancy patterns in order to be more effective. Since schools are used mostly during the cold months of the year, architectural strategies that improve the building performance through cold months are important. One of the effective strategies to increase the solar radiation through building envelope is to use sloped walls on the south side of the building. Also effective shading has to be considered in order to prevent overheating during warm months. Using 20° sloped walls on the south side of the building reduces the primary energy demand 7% in comparison to the building under the same condition with vertical south walls (fig.17).

Group three: Optimum external shadings and optimum school plan shape are the third priorities. The optimum shadings are defined so that to prevent over heating in warm months and allowing sun penetration in cold months of the year. Since inappropriate external sun shadings can block day lighting and decrease the daylight factor, it is essential to consider daylight factor during the simulation process. In Iran the schools' plans are designed and built in low diversity. The majority of the school building plans can be categorized in six typologies. These typologies have been modeled and their primary energy demand has been calculated and compared to each other. The findings show that the linear-shape and the U- shape plans have the minimum primary energy demand in comparison to other shapes (fig.14). Also the projection of the U-shape is analyzed through various simulations and the results show that 30% projection of the building length is the optimum projection for the U-shape. The U-shape school plan decreases the cooling energy demand due to the shading provided by the left and right wings of the building in summer. The heating energy demand has increased in comparison to the linear- plan due to the heat loss and also shading caused by the left and right wings in winter.

Group four: The optimum roof form, compactness of the school building form and the optimum class arrangements are considered as the architectural strategies that have the minimum impact on reducing the primary energy demand in the studied school building. The optimum roof form defined was a north 10° sloped roof. The roof slope direction is coordinated with the dominant wind direction, which is effective in reducing the cooling energy demand. This strategy reduced the primary energy demand 3% in comparison to the building under the same condition with a flat roof. The compactness of the building which is the result of omitting the side projection of the building has reduced the primary energy demand 3% in comparison to the existing building form. Also optimum class arrangements reduced the primary energy demand but the reduction is not tangible in the studied case. Not only does the arrangement of classrooms on the north side of the building provide appropriate daylight for learning, but also the sun penetration in the corridor is not disturbing and in warm months opening the doors and windows of the corridors and classes will promote cross ventilation.

5. Summary & Conclusion

Architectural strategies have an important impact on reducing the primary energy demand in buildings. In this study various architectural strategies were investigated and assessed in order to define the most effective energy saving architectural strategies in the studied school building. The results show that only by assigning optimum architectural strategies the lighting energy demand has been reduced 42%, the heating energy demand 11% and the cooling energy demand 47% in comparison to the existing school building with thermal insulation and the defined infiltration rate. The optimum amounts of all parameters are assigned in one model and the primary energy demand has been compared to the base case model. Results show that the primary energy demand has decreased 31% only by optimum architectural strategies, without any change in the building materials and construction parameters. This reduction is increased to 40% by considering construction parameters (insulating the thermal envelope due to the recommended regulations and decreasing the infiltration rate). Also the average indoor temperature was decreased by 3°C during warm months and increased by 2°C during cold months when mechanical heating and cooling systems were turned off . The architectural strategies defined in this study can be used in other school buildings in hot and dry climates. This method of architectural energy efficiency can also be applied in schools in the other climates.

Notes:

1. The primary coefficient for natural gas is 1.1 and 3.6 for electricity in Iran [25].
2. Total Solar Heat Gain Coefficient (SHGC): 0.819, Light Transmittance: 0.881.
3. HVAC COP. 40% for heating and 50% for cooling.
4. (0°) is defined as the south orientation and the building has been orientated clockwise.

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