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Original Article

Towards the Development of Energy Efficient Compact House: The Solar Decathlon SLIDE-S Prototype – Wall System design

Etman, Mohamed Aly[1], Tarabieh, Khaled[2], Bauriedel, Christian[3], Kazamel, Maya[2]

[1]Rensselaer Polytechnic Institute, [2]American University in Cairo, [3]Augsburg University of Applied Sciences

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Corresponding author:
Khaled Tarabieh, School of Sciences and Engineering, AUC, Email: ktarabieh@aucegypt.edu, Tel: 1094710280

Abstract

This paper discusses the envelope energy performance during the development stage for a Solar Decathlon prototype SLIDE-S (Sustainable Livable Individually-customized Design) SLIDE-S is a 72 m^2 residential house. It runs on solar energy during the day, and the final energy balance is zero. Inspired by the "*Mashrabiya*" in Islamic Cairo and the interlocking pattern of stones, the main features of the house are the *Voronoi* pattern which composes the structure and screen and the movable double screen which ensures adequate daylight is permitted. The main configuration of the house is its "*matchbox*" sliding configuration in which part of the screen moves out to allow direct light into the residential unit as well as enlarge the space covered by the house. The aim of this paper is to investigate the strategies mentioned above and through a series of simulation experiments and to examine how effective they are to deliver a zero-energy house. Using energy simulation, design recommendations are proposed to enhance the thermal performance of the skin and as a result, the overall design of the house.

I. INTRODUCTION

The U.S. Department of Energy Solar Decathlon (SD) is an award-winning program that challenges collegiate teams to design, build and operate solar-powered houses that are cost-effective, energy-efficient and attractive. The resulting homes demonstrate to students, the public, and industry that solar-powered houses are fully functional, comfortable and sustainable living spaces. SD aims to promote collaboration in the solar industry and to facilitate innovation and adoption of solar energy and energy-efficiency technologies. The competition started 2002 on a biannual basis; it was offered by the U.S. Department of Energy and organized by the National Renewable Energy Laboratory (NREL). European and Chinese versions were launched 2007 and 2011, respectively. Twenty universities from around the world are selected to design, build and operate an energy efficient house using the available renewable resources. The winning team scored the top on selected criteria and the most points in ten contests."[1]. SLIDE-S was a residential prototype exclusively designed for a temperate and hot-arid weather zones and developed by the American University in Cairo (AUC) Architecture and Construction Engineering Team. The emphasis in the design of this prototype is energy consumption and adaptability to the hot-arid weather. This paper is focused on the envelope testing of three wall systems; solid "*mass*" walls, air gap "*cavity*" walls and insulation "*thermal barrier*" walls to determine the best suitable envelope for the residential unit and the best energy performance of the prototype.

It is well known that the external wall envelope receive large amounts of solar radiation. In order to reach the desired thermal comfort conditions, walls heat storage capacity and heat conduction property are a key factor. Different wall properties; thickness, material, and finishes, can be chosen based on the heating and cooling energy requirements, having a significant effect. The thermal performance of a building envelope is dependent on the type and thickness of installed insulation and a number of other factors that are directly or indirectly related to the overall performance of the building skin. Among these factors are the thermal bridging, climate, ventilation and workmanship[2-7]. To better understand the behavior of the skin, different types of experimental testing methods were developed along with a recent reliance on parametric analysis and simulation for prediction of performance without in-situ experimental design[8-13].

Searching for the proper thermal insulation and air cavities in walls to reduce heat infiltration into the building is a primary aim for researchers, especially in hot regions. Panyu Zhu *et al.*[14] studied changing thickness and material of insulation layers directly to improve the heat transfer coefficient of the external wall. The study created a formula which was used to calculate the optimum thickness of thermal insulation layer for the exterior wall for five different cities in China representing different climatic conditions. The results showed that there is great potential for the envelop material in each climate zone to reduce heating and cooling demand by increasing the thickness of insulation layer and using better material. The average cost reduced yearly reached of EPS (Expanded Polystyrene insulation) from the required value to the optimum value. As for hot-arid environments such as the city of Riyadh, Saudi Arabia, Sami Al-Sanea and M. Zedan[15] studied numerically with an optimized insulation thickness of the dynamic thermal characteristics of insulated building walls with same thermal mass. The insulations explored the effect of using one, two and three layers of insulation, the locations of which are varied to achieve the best performance. About 20% decrease in both peak cooling and heating transmission loads were obtained. Another paper in the same weather zone focused on the evaluation of building envelopes in Dhahran and Riyadh in Saudi Arabia which are both extremely hot climates. This is mainly in response to the high energy consumption of residential building caused by poor envelope performance. Saleh *et al.* investigated the residential envelop design for hot climates, Dhahran and Riyadh, Saudi Arabia. A combination of four roof types and five different walls created eight different envelop designs. They were tested using VisualDOE 4.1 and insulation achieved 20% reduction in energy in comparison to the International Energy Conservation Code proposed design. Results were compared with building codes in both Riyadh and Dhahran[16].

In the Tunisian climate, both heating in winter and cooling in summer are required to reach comfort levels. In a study done by Naouel Daouas, searching for optimum insulation thickness, energy saving and payback period are calculated for a typical wall structure based on both cooling and heating loads. The results of a life-cycle cost analysis over a building lifetime of 30 years showed that up to 70% of energy savings and a payback period of 3.29 years for the south facing wall could be achieved[17].

The proposed sliding wall system matches the characteristics of a double skin façade. A number of studies recommended few treatments to minimize heat gain. A paper focused on the development of a universal lumped model to predict the performance of naturally ventilated double skin facades dealing with the current limitations of existing lumped models. The model is tested with an existing double skin façade in Beijing, and it is found to generate a maximum error of approximately 25%. The paper recommended that heat gain can be reduced by placing cavity shading closer to inside glazing[18]. A similar research focused on the Mediterranean weather zone studied a double-skin facade to see how the cavity width and depth affected specific cooling and heating loads in two typologies in Barcelona. Cavity widths were 40, 60, 80 and 100 cm; three different opening areas for ventilating cavities were experimented and the typologies were a corridor and a multi-story facade. The simulation was carried out with TAS software, and the building had a square floor plan; oriented along the four main solar orientations. All walls were opaque except for the South which was double-glazed[19].

Concerning the impact of insulation and thermal mass, some studies recommended the envelope system and methods of assessment. A study related to the context of the Australian building code, focusing on the effect of thermal mass on the energy load of a building was published. It proposed a new mass enhanced R-value that can be used to demonstrate code compliance. This is used to carry out tests on a BESTEST type model of a concrete sandwich panel wall so that its mass effect can be accounted for[20]. The influence of thermal mass was evaluated in a study that dealt with the effect of thermal mass on interior conditions considering three different buildings built primarily with timber, steel or concrete. Each was tested with two thermal envelopes, one meeting the minimum requirements of the New Zealand building code and one meeting industry "best practices." The aim was to find out the effect of thermal mass on HVAC systems over the life cycle of the building. Virtual Environment was used for simulations. Results indicated that thermal mass had relatively no impact on operational energy consumption in that climate but superior insulation required higher thermal mass to avoid a sudden energy increase indoors[21].

Finally, concerning the issue of assessment in warm environments, a study examined the effect of a cavity wall on the Sol-air temperature of the exterior wall and its effectiveness as a shading device. This was done through direct monitoring of the South-facing cavity walls on a house in a housing development in South Arizona. Site climate, building surface, and air moisture and temperature were recorded, their accuracy was verified, and the effectiveness of the cavity wall in both instances was proven. Energy-10 was used to estimate the effect of the cavity wall on the energy consumption of the house[22].

II. OBJECTIVE

This research aims to quantify and evaluate the effect of building envelope wall systems and materials on the energy consumption in air-conditioned compact residential units located in Egypt in different environments taking into account heating, cooling, plug loads and lighting fixtures.

III. THE EGYPTIAN SOLAR DECATHLON HOUSE - (BASELINE CASE)

The base case was chosen to be the first Egyptian solar decathlon house. The solar decathlon is an international student competition for designing and building a full-size solar-powered house. The SLIDE-S house was submitted and selected for both the solar decathlon Europe 2012[11-23] and the solar decathlon China 2013[12] editions (Additional information on the SLIDE-S team participation in the competition can be located at the following links:

- <https://www.solardecathlon.gov/blog/archives/611>
- <http://www.sdeurope.org/wp-content/uploads/downloads/2011/06/dossier-equipos-SDE2012_-dossier-teams-SDE201211.pdf>
- <http://sdchina.org.cn/english/history/2013/team/1#hs>

3.1. Base case design features

The Egyptian solar decathlon house design "SLIDE-S" (Sustainable Livable Individually-customized Design) is a project built upon the idea of a sustainable 'self-adjusting unit.' The aim of this design is providing the needs of sustainability while maintaining a low level of energy consumption via traditional passive techniques. A "matchbox" sliding configuration offers flexibility and provides shading and enclosure options for the house. This creates the basis of interactive, user-friendly responsive design. The SLIDE-S team decided to develop a contemporary form while preserving the Egyptian cultural features. The "*Mashrabia*" and the "*Magaz*" were found to be the key maintain the essence of an Egyptian residential unit (Fig.1).

Fig. 1: Exterior of the base-case (slides house).

The design was meant to be as simple as possible. The form generated is as compact as possible. A rectangular form allows for minimizing external surface area means minimum solar exposure. The house operates under a sliding "*matchbox*" configuration. This is achieved via a perforated skin composed of a lighter material taking the form of a three-sided screen that fits into the geometry of the house. This aims to optimize façade requirements as shading can be directly controlled by the user. During winter months, the shed like structure is slid into its open configuration so as to maximize solar gain through the southern glass façade. During summer, the shed is closed creating an additional skin layer that minimizes heat gain and shades the house allowing it to maintain a more comfortable interior environment. This flexibility in design allows for different levels of response to various climate fluctuations yielding optimization (Fig.2).

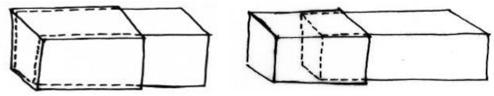

Fig. 2: Open "matchbox" configuration and closed "matchbox" configuration.

The interior space is divided into three main zones-a private, public and semi-public. The bedroom and workspace zone are elevated in order to achieve wider view angles into the house and separate it from the rest of the house. Having the natural lighting controlled using light screens "*Mashrabia*" reinforced in the matchbox structure also reflects the oriental architecture presented in a contemporary form (Fig.3). The modern form is generated using a Voronoi pattern using parametric design tools[24, 25].

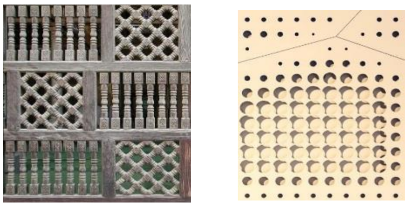

Fig. 3: Traditional screen (Mashrabia) and proposed contemporary screen.

The market idea of the house is that clients can customize their home on a particular website, according to size, spaces, materials, outfit, and parallel always aware of the total costs. This idea is already realized on websites of different car manufacturers[26, 27]. By entering the location of the client, the parametric model should automatically produce an optimized design according to the local climatic conditions of the customer. Therefore, the following paper investigates different envelopes in various locations.

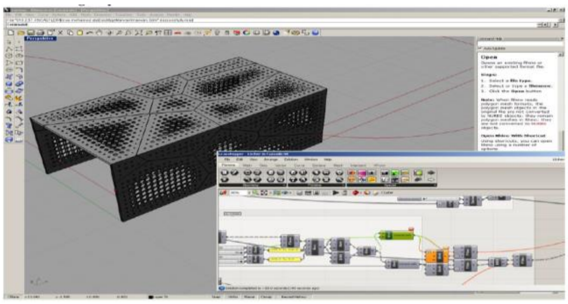

Fig. 4: Parametric Grasshopper model of the structure and the screen.

A Delaunay Triangulation divides the envelop of the house, and a Voronoi Diagram is generated (Fig.4), which is the base for the skeleton of the house and the divisions of the facade. The Voronoi-skeleton and the façade openings, located between the panels, are optimized by Genetic Algorithms. The skeleton in a structural way, sound statics with minimum weight and the façade screen energetically, what means that the solar impact in the summer is minimized by maintaining a maximum view from inside to outside at the same time. The design also implements a passive heating and cooling system using solar screens, as well as having the flooring of the house act as a thermal mass. Low levels of energy consumptions are maintained by selecting energy efficient appliances and lighting systems and depending substantially on natural light during the day, while to minimize the water consumption, water recycling is applied using a gray water system by which recycled water is used for irrigation purposes around the house.

3.2. Base case design parameters

The House is mainly divided into two zones separated by a semi-private circulation and service space that connects the North and South Facades. The inclined entrance inspired from the traditional "*Magaz*" provides privacy to the users of the house. The kitchen counter is located in the heart of the home acting as a hot spot that emits heat to other branches of the house. It also shapes the circulation of the house. The bedroom is located on the Eastern façade allowing for more privacy to the user since openings are limited. It is elevated at the height of 0.6m granting the space a higher sense of enclosure. This elevation also allows for greater view angles into the house. The bathroom is conveniently located within the same area as both the bedroom and the more public zone as well. The living space is located on the Western Façade so that when the shed structure is extended, an outdoor semi-enclosed area is created so as to form a seamless integration between the interior and exterior environment (Fig. 5). This configuration also allows Southern Sun exposure to heat and illuminate the room, while still maintaining privacy.

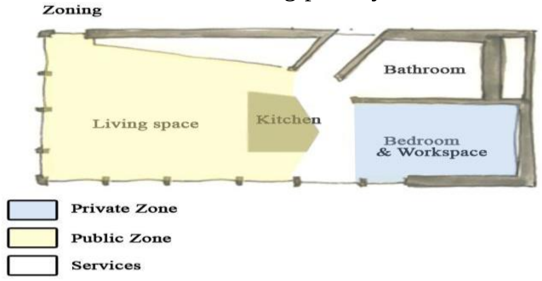

Fig. 5: SLIDE-S schematic layout.

3.3. Electrical loads

The electrical loads assigned to the house are the essential one to sustain a comfortable life. Furthermore, the solar decathlon competition has an appliances contest which is designed to mimic the appliance use of an average home. Points are earned for refrigerating and freezing food, washing and drying laundry, and running the dishwasher, performing all the daily life house activities. Accordingly, to the list of the appliances used, the average monthly loads installed are shown below in (Table 1). As for the lighting loads, an amount of $10 w/m^2$ is assigned to the house (A number of assumptions were based on historical information taking into consideration other model types presented in previous Solar Decathlon competitions). Three lighting control sensors are placed, the first on the kitchen counter, the second at the bedroom study desk and the third by the living couch with a 200 Lux minimum setting at 1 m height.

Table 1: Appliances loads used by SLIDE-S.

Appliance	Average Monthly kWh	Yearly Average Load (kW)
Clothes Dryer-Electric	36	432
Washer	29.4	352.8
Dishwasher	7.2	86.4
Hood	22	264
Oven	18	216
Cooktop	60	720
Refrigerator	33.12	397.44
LCD TV 32"	9.2	110.4
Laptop	4	48
DVD	3	36
Water Pumps	22.35	268.2
Control System	20	240
Sum	384.51	6927.75

IIII. METHEDOLOGY

The analysis was performed for the building envelope. The effect of the wall was addressed by comparing the energy consumption of different cross section was calculated and compared accordingly. The effect of wall thickness was analyzed by comparing the energy consumption of each one. The first step taken in the energy analysis was to calculate the thermal load of the base-case design. The thermal load of the house is measured by the amount of necessary power consumed while running the heating and cooling equipment to meet indoor comfort levels. The energy loads result assisted in selecting the appropriate materials for wall insulation. The aim is to calculate the energy consumption regarding cooling, heating, lighting and equipment loads. The cases were modeled within Rhinoceros CAD NURBS modeling software. The Diva-for-Rhino plug-in[28] was used to interfacing the EnergyPlus (v7.2) software which was used as a validated and tested energy consumption simulation engine.

V. PARAMETERS

Energy simulation was performed for five different cities: Alexandria, Cairo, Hurghada, Kharga, and Luxor. They were classified as Medetranian and hot-arid desert according to Köppen-Geiger climate classification [15]. However, there are differences between these cities regarding temperature ranges despite being of the same classification. Temperature is higher in Kharga all year round, especially in the winter time where it reaches about 30°C. Cairo temperature is higher than Alexandria, especially in summer (Fig. 4).

To evaluate the performance of the solar house, the construction materials of all surfaces were assumed as illustrated in (Table 2). The occupancy rate used was set to 10 m^2/ occupant. Heating and cooling set points and setbacks were assigned to be 22°C/12°C and 24°C/28°C, respectively. Lighting control sensors were placed at the location of the lighting fixtures with a 200 Lux minimum setting at 1 m height. The yearly energy consumption of each case was calculated by measuring the summation of the software output monthly cooling, heating, lighting and equipment consumption values using an ideal load mechanical system.

Table 2: The examined parameters used for the Base case simulation.

	Space Parameters	
	Floor level	Zero level
	Dimensions (m)	5.20 * 13.20 * 4.50
Walls	Construction Material	Plaster and paint (*2.5cm*) Double Brick Wall *(25 cm)*
Walls	U-value (W/m^2-K)	0.319
Roof	Construction Material	Reinforced concrete with R-15
Roof	U-value (W/m^2-K)	0.067
Floor	Construction Material	Concrete slab with R -14.6
Floor	U-value (W/m^2-K)	0.068

Glazing Parameters					
Orientation	North	South	East	West	Roof
Window to Wall Ratio (WWR)	13.4%	60%	3.8%	85%	33.2%
Area (m^2)	8	36	0.9	18.4	22.8
Thermal Properties	Single Clear Glass 6mm				
U-value (W/m^2-K)	6.121				

Three wall types are investigated in this paper. The walls are composed of a core of a double brick wall with a layer of plaster and paint on each side (2.5 cm). The thickness of the core layer is the primary parameter tested. The first one is the solid "mass" wall starting from 25cm to 45cm having an interval of 5cm. The second one is the cavity wall type having the core layer with an air gap. The cavity centered layer start from 5cm till 20cm with 5cm increment. The third type which is the insulated one has an insulation layer also starting from 5cm till 20cm. The tested parameters formed twelve different wall sections compared with the base-case original simple one.

VI. RESULTS

6.1. Cairo

Results in 'Cairo' using the insulated type showed significant savings starting from 3.6% (5cm insulation layer) to 5.1% (20cm insulation layer). The Air-gap type had 1.6% for the 5cm layer reaching 3.0% for the 20cm one, while the solid wall type reached only 0.9% for the 45cm core layer. (Fig.6).

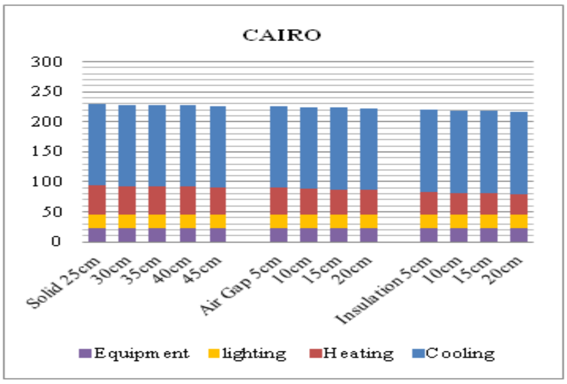

Fig. 6: Cairo annual energy consumed loads in kWh/m^2

6.2. Alexandria

As for Alexandria using the insulated type had savings starting from 3.4% (5cm insulation layer) to 4.8% (20cm insulation layer). The Air-gap type had 1.5% for the 5cm layer reaching 2.7% for the 20cm one, while the solid wall type reached only 0.7% for the 45cm core layer. (Fig. 7).

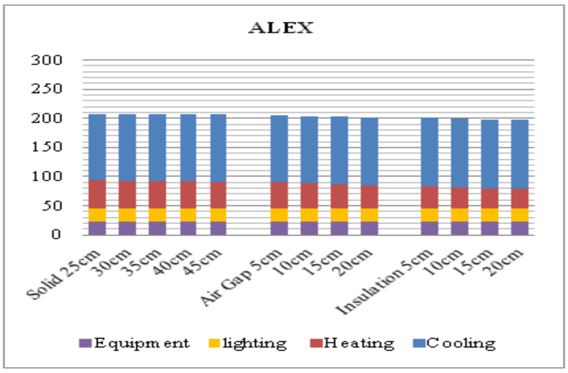

Fig. 7: Alexandria annual energy consumed loads in kWh/m^2.

6.3. Kharga

In Kharga, the insulated type had savings starting from 3.1% (5cm insulation layer) to 4.4% (20cm insulation layer). The Air-gap type had 1.3% for the 5cm layer reaching 2.4% for the 20cm one, while the solid wall type reached only 0.8% for the 45cm core layer. (Fig.8).

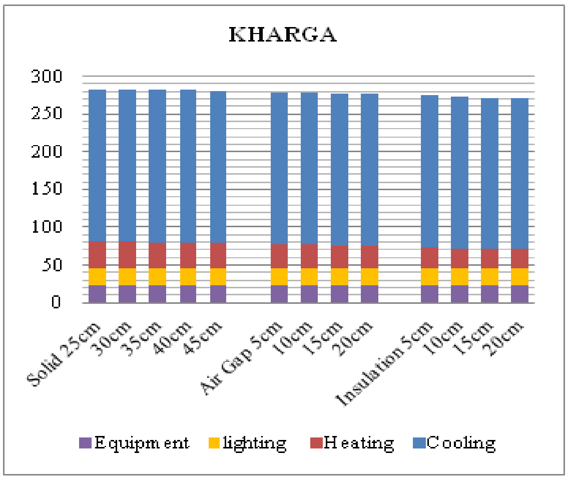

Fig. 8: Kharga annual energy consumed loads in kWh/m^2.

6.4. Hurghada

Hurghada simulations the solid type had only 0.4% (45cm core layer) savings compared to the base case 25cm brick wall. As for the insulated type, the savings started from 1.9% (5cm insulation layer) achieving only 2.7% (20cm insulation layer). The Air-gap type had 0.8% for the 5cm layer reaching 1.5% for the 20cm one. (Fig. 9).

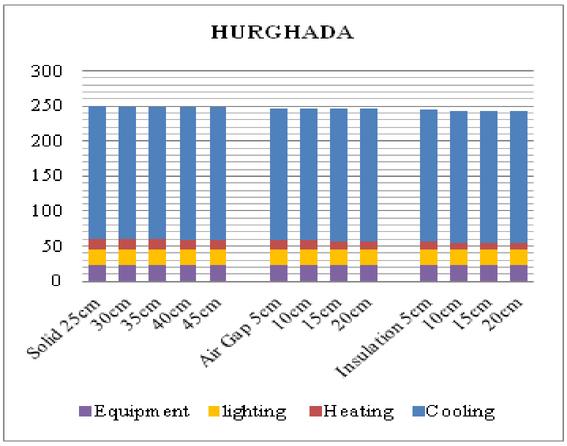

Fig. 9: Hurghada annual energy consumed loads in kWh/m^2

6.5. Luxur

In Luxor, the solid type had 0.7% (45cm core layer) savings compared to the base case 25cm brick wall. As for the insulated type, the savings started from 2.9% (5cm insulation layer) achieving only 4.1% (20cm insulation layer). The Air-gap type had 1.2% for the 5cm layer reaching 2.2% for the 20cm one. (Fig.10)

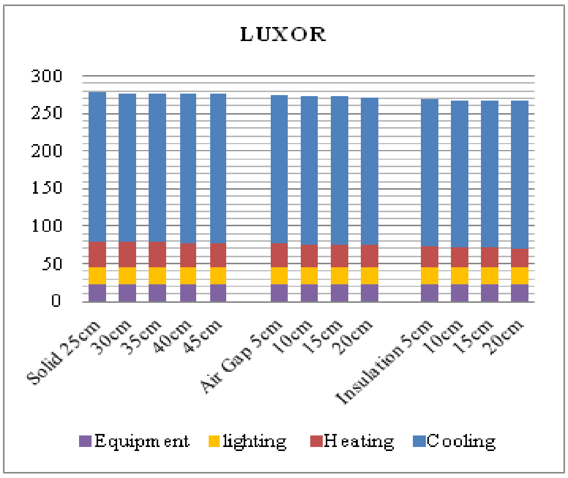

Fig. 10: Luxor annual energy consumed loads in kWh/m^2.

VII. DISCUSSION AND CONCLUSION

The research method analyzed the building envelope and the effect of the wall type was addressed using a comparative study to quantify the performance of different wall systems using simulation tools. The results mentioned above highlighted that the insulation is more efficient in the five tested cities. The savings were directly proportional to the thickness of the insulation layer used. Another research will be needed to investigate the return back period versus the initial insulation cost. The air gap layer also showed great potential if compared to the solid wall type (Fig.11) is cheaper and more efficient than the solid wall type.

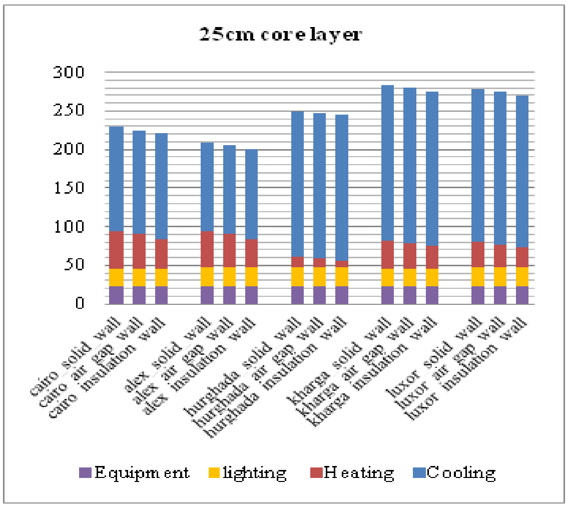

Fig. 11: Comparison of the annual energy consumed loads in kWh/m^2 for the tested sites.

For the solar decathlon Slides house, the cost, the weight and the thickness of the envelope is a major factor. A comparison concentrating on the 25cm thick wall of the three different types is made to identify the best option to be advice for the tested cities shown in Figure 10. The air gap type showed almost half the savings made by the insulation type. The insulation in Cairo city has the biggest amount of savings (3.6%) followed by Alexandria (3.4%)

and Kharga (3.1%). Then Luxor and Hurghada had only 2.9% and 1.9% saving, respectively. The air gap wall (5cm) reduced the energy consumed in Cairo by 1.6% followed by Alexandria with 1.5%, Kharga with 1.3%, Luxor 1.2% and at the end Hurghada did not save 0.8%. While the paper may carry few generalizations, it is recommended to carry further studies using detailed wall testing to validate the simulation results. The comprehensive wall testing can be performed using Standards such as the Test Methods for Thermal Performance of Building Materials and Envelope Assemblies. It should be noted that preliminary cost estimates of the different wall systems were studied but not in detail and will be further studied in depth in the future. In addition to cost, workmanship and constructability issues were also additional issues that were identified and required further studies to make sure the selected wall system is the best application given the market constraints. Finally, the energy simulation studies performed are focused on the envelope thermal performance only, other factors such as the air infiltration issues will need to be investigated in detail once the wall system and window design are confirmed.

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