Intelligent tall building envelope technologies and design alternatives for comfort and energy efficiency in hot, arid climate

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Abstract

Building envelopes function as an environmental filters: they form a skin around the building and control the influence of the outdoor environment. In a hot arid climate, due to problems such as overheating and high solar gain, intelligent design strategies and technologies for building envelope are necessary. More than one third of energy is consumed in buildings, more than in industry or transport, and the absolute figure is rising fast as the construction booms, especially in countries like UAE. Tall office buildings need attention due to their large size, energy consumption for cooling and lighting, and highly glazed facades.

The study aims to develop an approach for intelligent building envelope design for office buildings in hot, arid climate in order to achieve thermal and visual comfort and energy efficiency. The study analysed the outdoor and indoor climatic conditions, to understand the problems of overheating, discomfort, and the energy needed to achieve indoor environment quality. The effects of different technologies and design alternatives on comfort and energy efficiency were evaluated for the early design stage using computer simulation programs. The evaluated technologies include: glazing performance, shading and solar control, insulation and thermal mass, and the design alternatives included: opaque to transparent ratio, orientation, and natural day and night ventilation. The results show the potential for a significant decrease in cooling loads and energy for lighting, and increase in thermal and visual comfort, if appropriate building envelope alternatives are evaluated and implemented in the early design stage. The study shows the need for a guidance methodology to integrate later simulation performance in the early design stage to achieve intelligent envelope design.

Keywords: Intelligent envelope, envelope technologies, design strategies, energy efficiency, hot arid climate

1. Introduction

1.1 Intelligent building envelope

Intelligent building envelope (also called advanced envelope, high performance envelope, innovative envelope, smart envelope, or responsive envelope) can be defined by its ability to adapt to a variable environment. Intelligence may be related to the responsive performance of the building envelope. According to Wigginton & Harris (2002) an intelligent building envelope may be defined as "a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort" (p. 27). Wong et al. (2008) suggested that intelligent envelopes need to respond to the change and to meet the requirement of the users. According to Compagno (2002) "an 'intelligent' facade is not characterized primarily by how much it is driven by technology, but instead by the interaction between the facade, the building's services and the environment" (cover). Building facades are of great importance since they function as an environmental filter: they form a skin around the building and control the influence of the outdoor environment. According to Hass and Amato (2006) they are responsible for around one third the building energy bills. Tall office buildings are getting predominant in the Middle East and attention should be paid to designing them, and especially their façades, in ecologically responsive way. All over the world the skylines are dominated by tall, glazed office buildings, but it is surprising that there is one single building form reputed appropriate for such different climates and cultures. According to Ochoa and Capeluto (2008) intelligent façade solutions in the hot arid climate have been barely studied compared with the growing knowledge for those in cold climate.

The climatic conditions in a hot, arid climate, characterized by high temperature and low humidity, make the use of passive façade solutions alone not enough to achieve comfort, especially when highly glazed façades are used: these require an early evaluation of their performances. Although there are many building performance simulation tools available, stated by Augenbroe et al. (2004), Crawley et al. (2008) and Hensen (2007), the simulation activity in the building design process is limited and mostly restricted to its final stages. Moreover, most simulations software used by the consultant and façade engineers - usually in the late phase of design - when the geometric characteristic of the building are fixed. In this stage, the ability to utilize the passive design alternatives may be restricted and mechanical conditioning systems are thus needed to maintain the occupancy comfort. However, the decisions made in the early design stage have the largest impact on comfort and energy performance, as highlighted by Ochoa and Capeluto (2008). For this reason, a guidance approach for the evaluation of the envelope solutions during the early phase of design process is necessary to put the tool in the hands of architects, so they can make informed decisions over the best envelope alternatives and take part in the optimization of building performance.

Although models have been proposed for the early design stage, they are used to evaluate finished alternatives and they are not suitable as a practical design guide, and none of them follows the logic of the architectural design process. According to Ochoa and Capeluto (2009) the decisions in this phase are based on general ideas and cannot be evaluated with tools to give exact results. There is a very limited guidance for architects to be able to understand and integrate the simulation performance in the early design stage.

1.2 Hot, arid climate

The study analyzed the outdoor condition in hot arid climate, to understand the problems of overheating and discomfort due to high temperature and solar radiation. In arid climates, the main problems the dry air with a large diurnal temperature variation, the low relative humidity and precipitation, and the high solar radiation: this leads to a very high risk of overheating. Analysis of the outdoor air temperature for five cities in the middle east region (Basra in Iraq, Kuwait city in Kuwait, Dubai in UAE, Doha in Qatar, and Riyadh in Saudi Arabia), shows extremely high temperatures, especially in summer time, when the average high temperature arrive at around 32-40°C. In addition, the difference between the average low and average high temperature is relatively high and it can range between 10-23°C as in figure (1). The analysis of the outdoor solar radiation for the five cities mentioned above shows the high solar radiation (monthly average) on the horizontal and vertical planes. The low relative humidity average for the major part of the year ranges between 20-50% measured at 3 PM for Riyadh city. For such arid climate, special consideration should be taken in the design phase to avoid the discomfort due to high temperature and arid context.

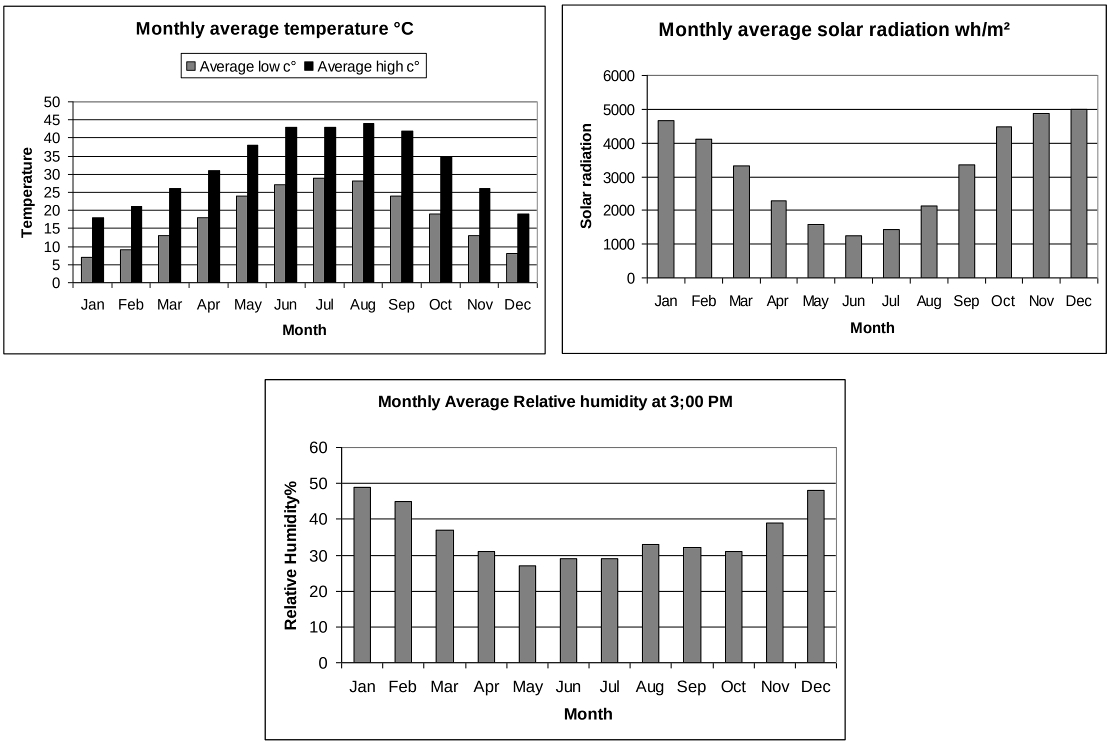

Figure 1: air temperature, solar radiation on south vertical plan and relative humidity for Riyadh, Saudi Arabia

It can be concluded that in April, May, June, October and November, shading, ventilation, thermal mass, and night ventilation can be effective tools in restoring comfort, while in July, August and September, the temperature is so high that conventional air conditioning is also needed for comfort. In December, January and February, solar radiation could be exploited for passive heating.

2. Methodology

The approach methodology consists of three phases, as illustrated in figure (2).

- Pre-processing

Defining the problem, design questions, the performance parameters, and the data needed in the early design stage. In this phase case studies were analysed to determine the appropriate technologies and design alternatives to be evaluated.

- Design decision analysis

Describing the scope of the performance simulation and validate the results through simulation tasks to obtain a numerical validation for the performance of different design alternatives. In this stage the simulation tools should be decided in order to achieve the desired requirements. The choice should be based on questions like: Can the tool analyse the problem? How easy is it to use? How easy is it to understand the results? Can CAD and other tools help? What data will be needed and are they available? How accurate are the results? What skills are needed in the early design team? How to validate the results?.

- Select the feasible design alternatives

The question here is how decision makers could select the best design alternative for a particular performance problem, since the objective of design decision-making is to determine the optimum values that define the best design alternative. Most of the time, it is not easy to pick a single design alternative as the best one, since design alternatives competes with each other across multiple design objectives.

Translating the simulation tasks into design criteria in the approach method, the process steps will guide the architects in driving productive information from the simulation activities to generate concepts, make decisions and select optimum solutions. Depending on the performance outcomes, the design can then be modified to achieve the desired performance. Variable parameters include changing the orientation, opaque to transparent ratio, insulation, thermal mass, the use of natural day and night ventilation, shading, light shelves, and the use of renewable solar and wind energy. The optimum solution can be chosen based on informed and exact evaluation decisions like: optimum orientation, windows size, U-value, R-value and wall thickness, thermal mass (heavyweight, medium-weight, and lightweight materials), shading elements, daylight elements, and the performance of renewable features.

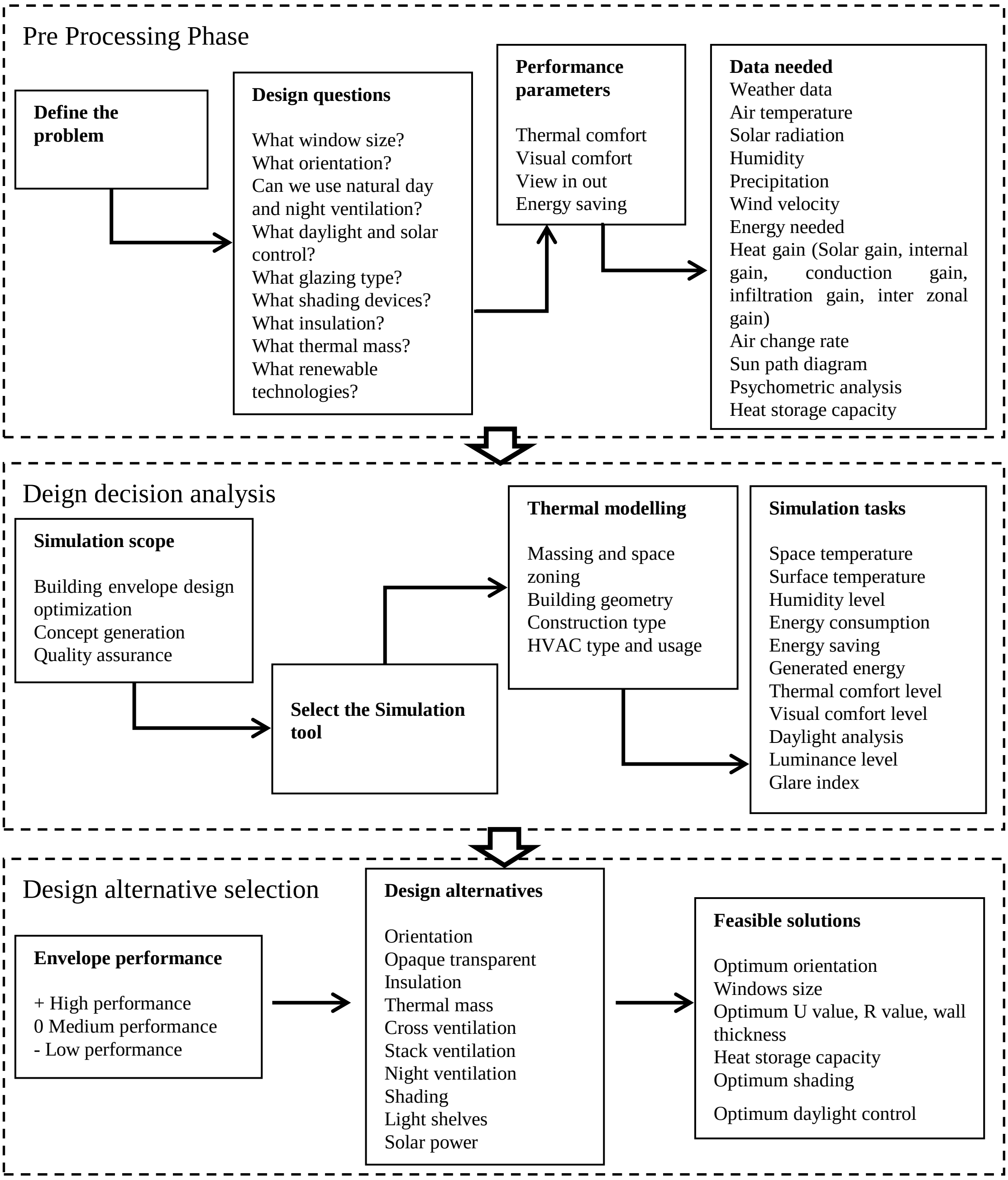

Figure 2: the approach methodology

The performance of passive design alternatives and active technologies has to be evaluated. The performance is evaluated to be (+) high performance, (0) medium performance, (-) low performance like in the matrix in table (1). This comparison matrix is built by a pair wise evaluation of each alternative and criterion. A priority ranking will be developed in the end, indicating the best solution of the defined problem.

Table 1: simulation performance parameters and alternative envelope design solutions

		Simulation performance parameters			
		Thermal comfort	*Visual comfort*	*View in out*	*Energy efficiency*
Intelligent envelope design	*Passive design strategies*				
	Façade technologies				
	Renewable				
	Integrated solutions				

3. Results and discussion

The results represent the first outcome of an on-going research aimed at finding guidance for the integration of building performance simulation in the early design stage of office buildings in hot, arid climate. The integration of simulation performance with envelope design will help the architect to make informed decisions in the early design stage and select the appropriate technologies and design alternatives. This paper presents the effects on building performance, while the simulation results are presented elsewhere at this conference.

3.1 Windows wall ratio and orientation

The use of large window areas can provide good daylight and a good view to the outside, but it may also increase the heat gain and the energy consumption for buildings with air-conditioning. Therefore, the windows play an important task by providing the buildings with daylight, view, ventilation, and moderate the heat gain / loss. The simulations were run for the different orientations and the following glazing ratios: 30%, 50%, 70% and 90%. The orientations considered are: south, north, east, west, 30º from N to E, 30 º from S to W, 60 º from N to E, 60 º from S to W, 30 º from N to W, 30 º from S to E, 60 º from N to W, 60 º from S to E. Table (2) shows the results translation into performance evaluation in terms of thermal, visual comfort and energy efficiency to be high, medium or low performance.

The results confirmed the traditional approach to reduce heat gain by reducing or increasing the total glazing area for different orientations. Large glazing areas are possible at north as the direct solar radiation passing through is limited. However the entry of diffuse light must be taken into account. Solar screening or solar control glazing can be provided in order to achieve a comfortable room climate in buildings with large window areas. The south façade receives its light at a steep angle, so the intensity of solar radiation on the façade is smaller, and efficient shade can be provided with little detrimental effect on daylight entry or view out. In summer, a large amount of solar radiation enters the east and west façades at a shallow angle, making it more difficult to design the solar screening to be efficient and let enough daylight into the room. Special screening technologies and glass are needed beside a windows / wall ratio consideration.

Table 2: Performance of glazing percent and orientation, (+) High performance, (0) Medium performance, and (-) Low performance

Orientation and Opaque transparent ratio		*Energy efficiency*	*Thermal comfort*	*Visual comfort – daylight*	*View in-out*
South	*30% glazing*	+	+	-	*0*
	50% glazing	*0*	*0*	+	+
	70% glazing	-	*0*	+	+
	90% glazing	-	-	+	+
North	*30% glazing*	+	-	-	*0*
	50% glazing	+	+	+	+
	70% glazing	+	+	+	+
	90% glazing	*0*	*0*	+	+
East	*30% glazing*	+	+	*0*	*0*
	50% glazing	*0*	*0*	-	+
	70% glazing	-	-	*0*	*0*
	90% glazing	-	-	*0*	*0*
West	*30% glazing*	+	+	*0*	*0*
	50% glazing	*0*	*0*	-	+
	70% glazing	-	-	*0*	*0*
	90% glazing	-	-	*0*	*0*

3.2 Natural day and night ventilation

Natural ventilation is one of the most important cooling techniques. In the majority of old buildings, infiltration levels were high enough to provide a considerable amount of outdoor air. In contemporary architecture and energy efficient buildings, designers have reduced air infiltration to the minimum to reduce its impact on the cooling and heating loads. Large glazed office buildings, which do not allow opening the windows, have a limited possibility to use natural ventilation to supply the indoor spaces with fresh air, which can reduce the cooling loads and enhance thermal comfort. On the other hand, studies of sick building syndrome (Gratia & Herde, 2007) indicate that perception of greater control over ventilation, lighting and temperature is associated with decreased prevalence of symptoms. Becker & Paciuk (2002) investigated the effects of cooling strategies and building features on energy performance of office buildings and found that, for buildings with large internal loads, intensive night pre-cooling is the most effective strategy for smoothing required power loads.

In hot, arid climates, where the cooling load is dominant, using natural ventilation is sensible only if ambient temperature is lower than the indoor temperature (Kubota et al., 2009). In office buildings, the rise in temperature will affect not only the air in the rooms: after some delay, the temperature of the furnishings, ceiling, walls, etc. will also rise. After working hours, large quantities of this stored daytime heat will still be present in the room and objects within it. In such a situation, relief can be obtained only through night ventilation with cooler air, allowing a natural heat purge of the unoccupied building through a controlled opening of windows or flaps.

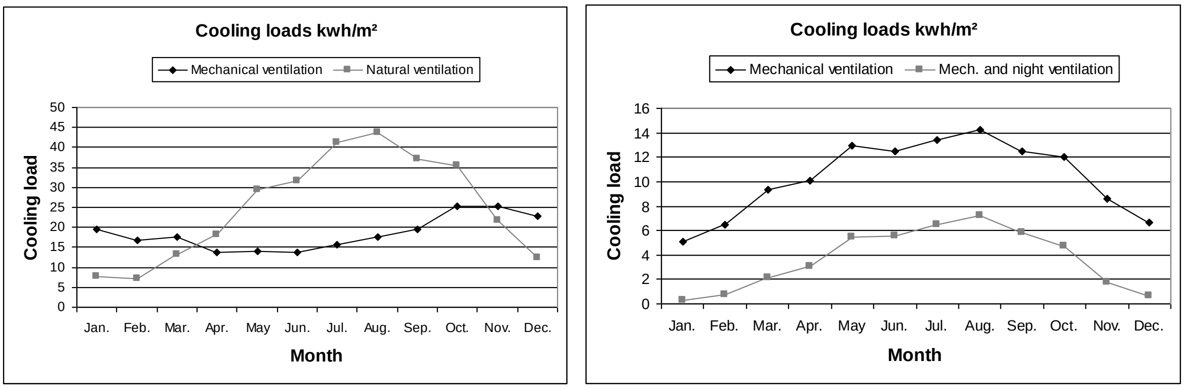

Figure 3: natural day and night ventilation strategy and its effect on cooling load

The simulation results for the use of daytime natural ventilation show positive effects on the cooling load only for a few months (January, February and December). Figure (3) left shows the cooling loads in Dubai, UAE when using mechanical and natural all-day ventilation. The simulation for the use of night ventilation for 3 hours in the early morning (2:00 AM to 5:00 AM) shows the great reduction in cooling loads around the year as in figure (3) right for Dubai, UAE. The simulation was done using TRNSYS software. In the first phase only mechanical ventilation was used and then night ventilation was applied for 3 hours in the early morning.

3.3 Glazing selection

In hot, arid climate, solar heat gain can contribute to the overheating of the building, and it can cause thermal discomfort or unnecessary load on refrigeration and air conditioning. Solar control glass usually either body tinted (absorbing) or coated (reflective) is often used to reduce unwanted solar gain. Glass performance for solar control can be modified adopting variations such as: body tinted, reflective coated, combination of body tinted and reflective coatings, and single and double glazed units. This high performance glazing admits as much daylight as possible, while preventing transmission of as much solar heat as possible. Switchable glazing is an attractive approach to solar control and daylight regulation in highly glazed building. At present, switchable reflective glazing is at the early stage of laboratory development.

The analyses where conducted for different locations in hot, arid climate, using simulation software TRNSYS, to evaluate the effects of various glazing types on thermal, visual comfort and energy efficiency as in table (3). The results show the influence of glazing selection on the envelope performance.

Table 3: Performance of glazing selection, (+) High performance, (0) Medium performance, and (-) Low performance

Glazing type	*U value, W/m² K*	*g value*	*Energy efficiency*	*Thermal comfort*	*Visual comfort – daylight*	*View in-out*
Single glazing	*5.8*	*0.855*	-	-	+	+
Double argon filled	*1.3*	*0.624*	*0*	*0*	+	+
Double glazing	*1.4*	*0.589*	*0*	*0*	+	+
Double tinted, gray	*1.3*	*0.397*	+	*0*	*0*	*0*
Double tinted, silver	*1.3*	*0.298*	+	+	*0*	-
Double tinted, gold	*1.3*	*0.212*	+	+	-	-
Reflective glazing	*2.1*	*0.27*	+	+	*0*	-
Active glazing			+	+	*0*	-

3.4 Shading

Solar control is one of the most important measures to avoid indoor overheating and discomfort, especially in hot climates. It prevents direct solar radiation from entering the building when it is not desirable. Shading devices should be selected according to the orientation of the windows. Moreover, in multi-story office buildings the occupancy and equipment’s gain are such that heating is rarely required, especially in hot climates. For these reasons, shading is required to completely protect windows all year-round. External shading devices are more effective than internal ones: internal shading devices are not recommended as they trap heat on the interior of the glass so it remains indoor, and they may have a negative effect on natural light conditions. A combination of exterior and interior shading devices is recommended in some cases to avoid glare from direct and indirect solar radiation. The simulations were done for different types of fixed and movable shading, evaluating their effects on the visual, thermal comfort and energy efficiency as indicated in table (4).

3.5 Insulation and thermal mass

Modern office buildings usually have high internal heat generation due to equipment in use, as well as many large windows. Internal thermal mass provided in floors and exterior walls can absorb and store solar radiation and internally generated heat, and thus keep the air temperature moderate. Moreover, thermal mass reduces heat gain in the structure by delaying the entry of heat into the building and storing heat, whether from the sun or the internal loads of the building.

The simulations were performed, using TRNSYS simulation software, for Riyadh, Saudi Arabia. The results indicate that the impact of the U value of envelope components in office buildings is not significant. It was found that adding wall insulation does not always reduce annual energy consumption and, in some cases, adding thermal insulation directly increases it. This can be justified by the internal gains from equipment, lighting and occupants. On the other hand, using high thermal mass materials combined with night-time natural ventilation has a positive effect on reducing the cooling loads and discomfort hours.

Table 4: Performance of shading selection, (+) High performance, (0) Medium performance, and (-) Low performance

Fixed and Operable Shading	*Orientation*	*Energy efficiency*	*Thermal comfort*	*Visual comfort and daylight*	*View in-out*
External projection and solar control	*South*	+	+	+	+
	East	-	-	*0*	+
	West	-	-	*0*	+
External vertical louvers	*South*	-	-	*0*	+
	East	+	+	*0*	*0*
	West	+	+	*0*	*0*
External horizontal louvers	*South*	+	+	+	*0*
	East	-	-	+	+
	West	*0*	*0*	+	+
Internal systems	*South*	+	+	*0*	-
	North	+	+	*0*	-
	East	*0*	*0*	*0*	-
	West	*0*	*0*	*0*	-
Eternal projection and internal systems	*South*	+	+	*0*	*0*
	North	+	+	*0*	*0*
	East	***0***	***0***	-	-
	West	***0***	***0***	-	-

4. Conclusions

This paper presents the first results of an on-going study which aims at finding design guidance for tall office building envelope in hot arid climates. The evaluation of different technologies and design alternatives for tall office buildings in hot, arid climates offers the opportunity to evaluate the alternative solutions in the early design stage. This guidance is suitable for architects and facades engineers willing to design low-energy, high-comfort buildings in cooling-driven climates.

The first results show the importance of different envelope technologies and design alternatives and their effects on building performance, and the importance of developing the design approach to evaluate the performance of the passive design alternatives and envelope technologies for office building envelope in hot, arid climates during the early design phase. The future work of this on-going study is to establish the guidance approach that integrates the simulation performance in the early design stage to achieve climate responsive envelopes design.

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