Envelope Design and Thermal Comfort Performance in a High-Rise Office Building in Saudi Arabia ‎

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**Abstract:** Thermal comfort is a key aspect when assessing a sustainable building’s ‎performance. In hot climates, such as Saudi Arabia, achieving comfort ‎can require large amounts of cooling energy if the building has not been designed to take ‎advantage of passive cooling techniques. In this study a thermal model of a real high-rise ‎office building in Saudi Arabia was created and used to predict internal air temperatures, ‎comfort levels and energy consumptions using *DesignBuilder®* software for summer days. ‎Field measurements of comfort levels and internal temperatures were taken in the actual ‎building to compare with the modelled data to check for acceptable agreement, and a small ‎thermal comfort survey with office workers was also undertaken. The as-built office model ‎was then parametrically altered for a range of passive strategies (including glazing area, ‎insulation levels and thermal mass) to identify the most effective approaches to reducing ‎cooling energy demand. ‎The study revealed that certain passive approaches improved thermal comfort and could be applied successfully whiste ‎maintaining an acceptable corporate image for the building.

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**Keywords**: Built Environment, Thermal Comfort, High-Rise buildings, Architecture Technology, Sustainable Buildings

# Introduction

Global warming and sustainable development have become key ‎issues for the built environment. Architects and engineers now need to consider any financial or environmental implications of their designs during the ‎building’s life (Holmes and Hacker, 2007). A key consideration in a sustainable strategy is the need to evaluate the role of fabric design efficiency and its impact on human thermal comfort. In countries with predominantly hot dry climates, such as Saudi Arabia, achieving thermal comfort ‎can require substantial amounts of cooling energy. This problem can be exacerbated by the design of the building’s external envelope. The appearance of many modern office buildings in Saudi Arabia resembles those seen in the USA or Europe, where the climates can be much less demanding in terms of thermal comfort. A first step in reducing the cooling energy demand of Saudi offices is to investigate the potential impacts that passive design measures applied to the building envelope, such as thermal insulation and thermal mass, can have in maintaining comfort whilst reducing cooling energy consumption.

This study used an actual office in Dhahran, Saudi Arabia to assess actual energy use and thermal comfort and then undertook a parametric analysis using a range of passive envelope measures. Summer conditions were chosen as they obviously represent the biggest test to the building envelope’s thermal cooling performance. The dynamic simulation software *DesignBuilder®* was used to predict hourly values of operative temperature inside a zone of the office building. Predicted values from *DesignBuilder®* were compared to monitored data from the observed office.

# Background

Saudi Arabia’s main sources of energy are oil and natural gas. The country burns more than one million barrels of oil per day to generate electricity (Alshehry and Belloumi, 2015). Electrical energy usage in Saudi Arabia has risen sharply in the last twenty-five years because of population growth, strong economic development and the lack of energy efficiency measures. Electricity consumption per capita in Saudi Arabia is approximately three time the global average (Naif, 2012). It has been estimated that around 73% of the electricity produced in Saudi Arabia is used in buildings, with 65% of that consumption being for air conditioning (Saudi Electricity Company, 2015).

There is now a growing interest and requirement to make Saudi buildings more sustainable. Measures such as developing local building codes, enforcing insulation usage and applying other sustainable treatments in construction have been considered in order to manage total building energy consumption. This approach includes any environmental friendly treatments during the design concept stage, the construction process and the building operation in order to conserve the environment (Mujeebu and Alshamrani, 2016). Mujeebu and Alshamrani (2016) also highlighted that US$26 billion has been invested in 76 green building projects across the country. This includes the King Abdullah financial district, which is one of mega green projects around the world. Furthermore, 90,000 eco-friendly mosques have been identified in the government’s plans across the country to adapt green buildings as a new choice of construction. Thus, Alyami and Rezgui (2012) suggested that the USA building standard LEED could provide the basis of a Saudi version in order to combine both national and local considerations.

Office buildings account for 14% of total building energy consumption in Saudi Arabia, and so are an important building type for energy efficiency design and retrofit (Al-Ghamdi et al, 2015; Alyousef and Abu-Ebid, 2012). In their review paper of 25 years of cooling research in office buildings, Prieto et al (2017) suggested that cooling research for offices in hot-arid climates was much less common than for offices in more temperate climates, but that this was changing. Recent projects have been undertaken in Middle East Gulf countries that have focussed on the evaluation of passive cooling strategies; for example, the energy performance of shading systems (Freeman, 2014), the evaluation of glazing properties (Bahaj et al, 2008), the effectiveness of multi-façade systems (Radhi et al, 2013) and the efficiency of passive envelope measures (Friess and Rakhshan, 2017).

This study has concentrated on passive envelope measures, such as thermal insulation and glazing specification. An actual office block in Saudi Arabia was identified and monitored. Then, aspects of the office’s envelope were parametrically altered and modelled to assess what impact the changes had on internal temperatures and thermal comfort conditions in the office.

Methodology

This study used thermal comfort performance as the metric to assess the impact of applying different passive envelope approaches to an existing high-rise office tower in Dhahran, ‎Saudi Arabia during severe climatic conditions in summer. Thermal comfort is defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) as “*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*” (ANSI-ASHRAE Standard 55, 2013). Ruppa et al (2015) reviewed the two basic ways of approaching thermal comfort in buildings – the Fanger model (1970) and the adaptive model (Nicol et al, 2012). This study has adopted the Fanger model (1970) as it is more relevant for air-conditioned spaces, such as those found in Saudi office buildings. Fanger’s model is quantified in terms of the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).  PMV relates to a seven point thermal scale that ranges from Cold (-3), through Neutral (0) to Hot (+3). The recommended acceptable PMV range for thermal comfort in ANSI-ASHRAE Standard 55 is between -0.5 and +0.5 for an interior space. PPD predicts the percentage of occupants that will be dissatisfied with the thermal conditions. PPD is a function of PMV, and as PMV moves away from 0 (neutral), PPD increases. Because thermal comfort is subjective then it is never possible for everyone in a space to be comfortable all of the time. In ANSI-ASHRAE Standard 55 the recommended acceptable range for thermal comfort is for PPD to be less than 10% for an interior space. The dynamic thermal modelling software ‎*Designbuilder®5.0* was used for this study as it is able to analyse energy consumption, comfort ‎levels and other built environment parameters on an annual, monthly, daily or hourly basis depending on the study’s requirements.

For this paper, a typical summer day was selected for the analysis and environmental assessment. The office building used in the study was located in Dhahran, Saudi Arabia, and was 13 storeys high. Figure 1 show the geometry of the simulated version of the building. The internal layout consisted of both open plan and cellular office spaces, and for the initial analysis an open plan office facing to the north – east, in the form shown in Figure 2, was selected.

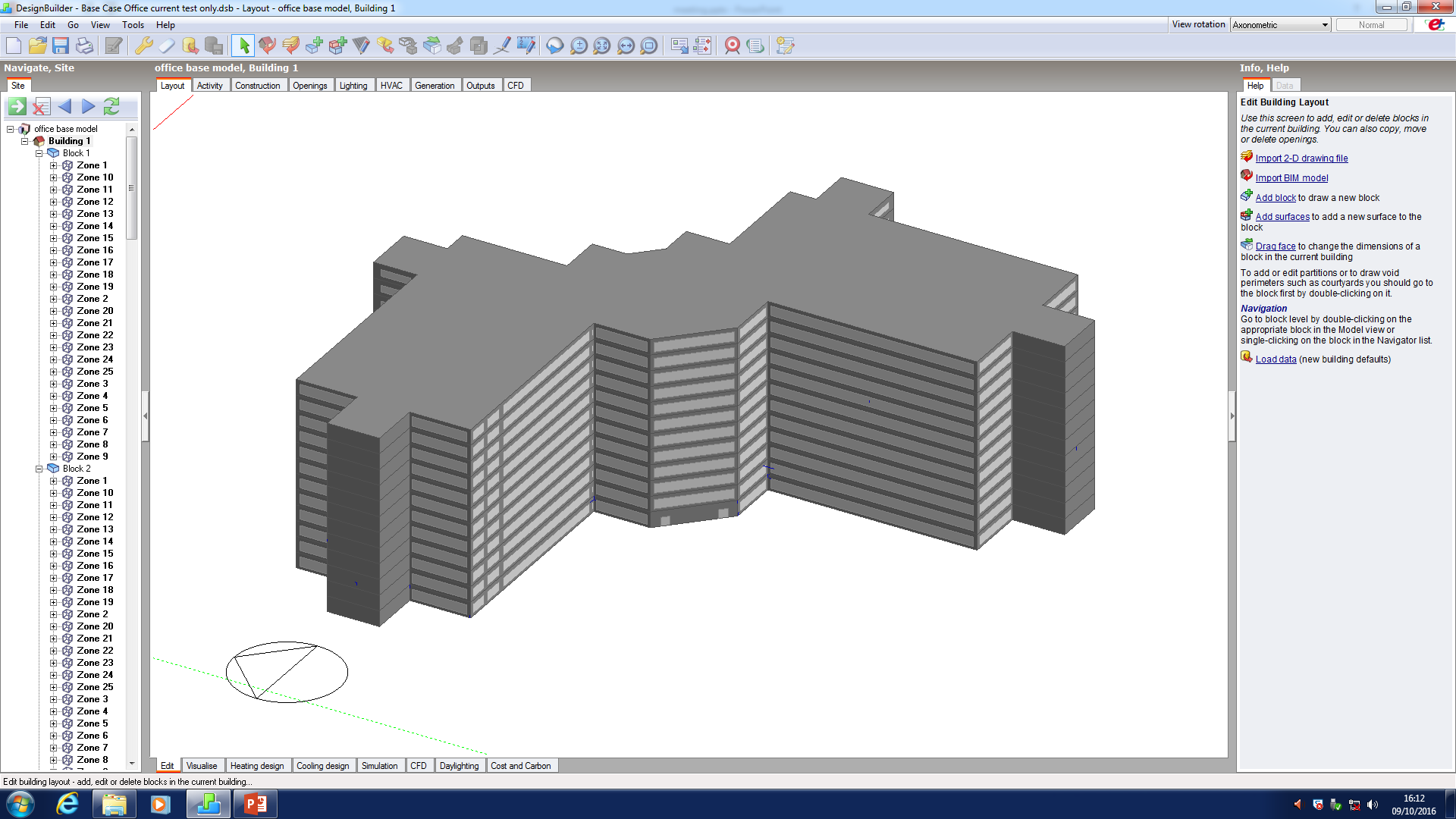


Figure 1.The geometry of the tested office building ‎

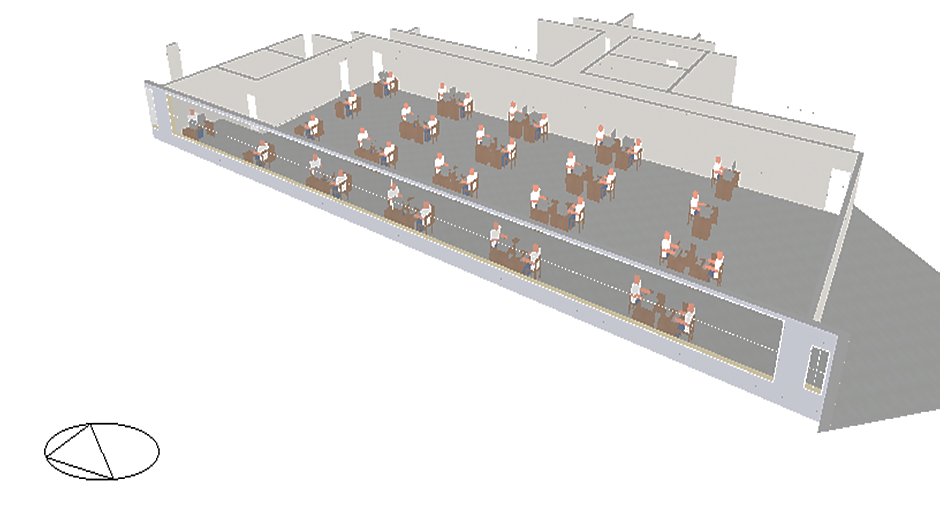


Figure 2.The selected zone of the study

The constructional and material details of the building were acquired from a site visit and Tinytag data loggers were positioned around the open plan office to measure air temperature and relative humidity levels over a two-week summer period. A virtual model of the office was created in *Designbuilder®5.0* and simulations of the predicted performance were undertaken. Data from the modelling were compared to the measured results from the dataloggers to check the *Designbuilder®5.0* model’s reliability. Finally, *Designbuilder®5.0* was used to make parametric changes to the existing office to see if thermal comfort performance could be improved by passive measures. The passive measure considered in this study were insulation thickness and choice of glazing system.

## Results

***Reliability of Designbuilder®5.0 model***

Table 1 shows a comparison between the measured and modelled data for the open plan office for one of the summer days. For the hottest part of the day, when the office is most used, the agreement is good. This indicates that the settings chosen in the *Designbuilder®5.0* model (such as occupancy profile and set point values) were appropriate. Validation of the *Designbuilder®5.0* model gives confidence for the parametric analysis.

Table 1. Sample of the compared temperature data between simulation and field measurement readings in open plan office – typical summer day in Dhahran , Saudi Arabia.

|  |  |  |  |
| --- | --- | --- | --- |
| Time | Measured  air temperature [°C] | Modelled  air temperature [°C] | Percentage difference (%) |
| 13:00 | 24.5 | 23.6 | 3.6 |
| 14:00 | 23.8 | 23.5 | 1.3 |
| 15:00 | 23.3 | 23.4 | -0.4 |
| 16:00 | 22.6 | 23.4 | -3.5 |

***Parametric analysis for thermal insulation***

Figure 3 shows the existing construction of the open plan office’s envelope (A), consisting of an external aluminium cladding, a 75mm air gap, 200mm concrete hollow block and a gypsum plasterboard internal finish of 12mm. For the parametric analysis increasing thicknesses of thermal insulation were inserted in to the air gap until the air gap was totally replaced by the insulation for the treated envelope (B).

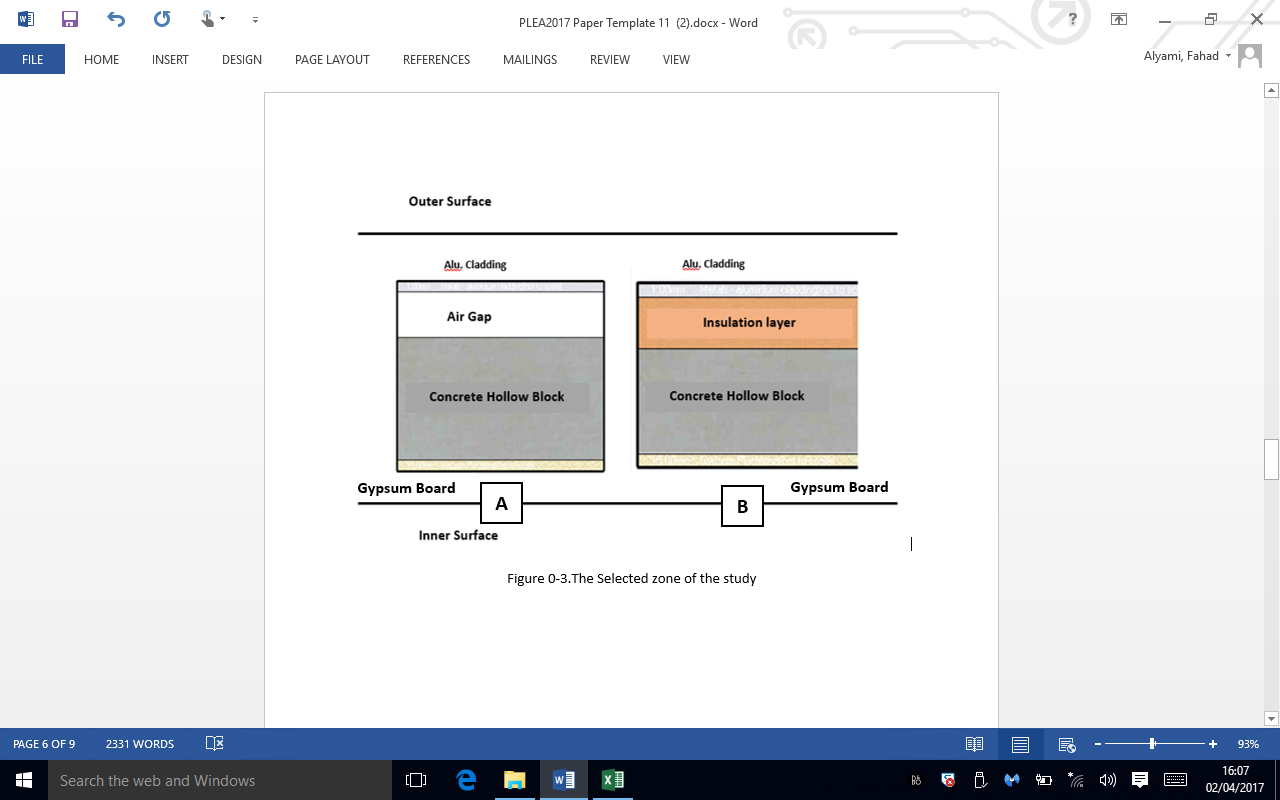
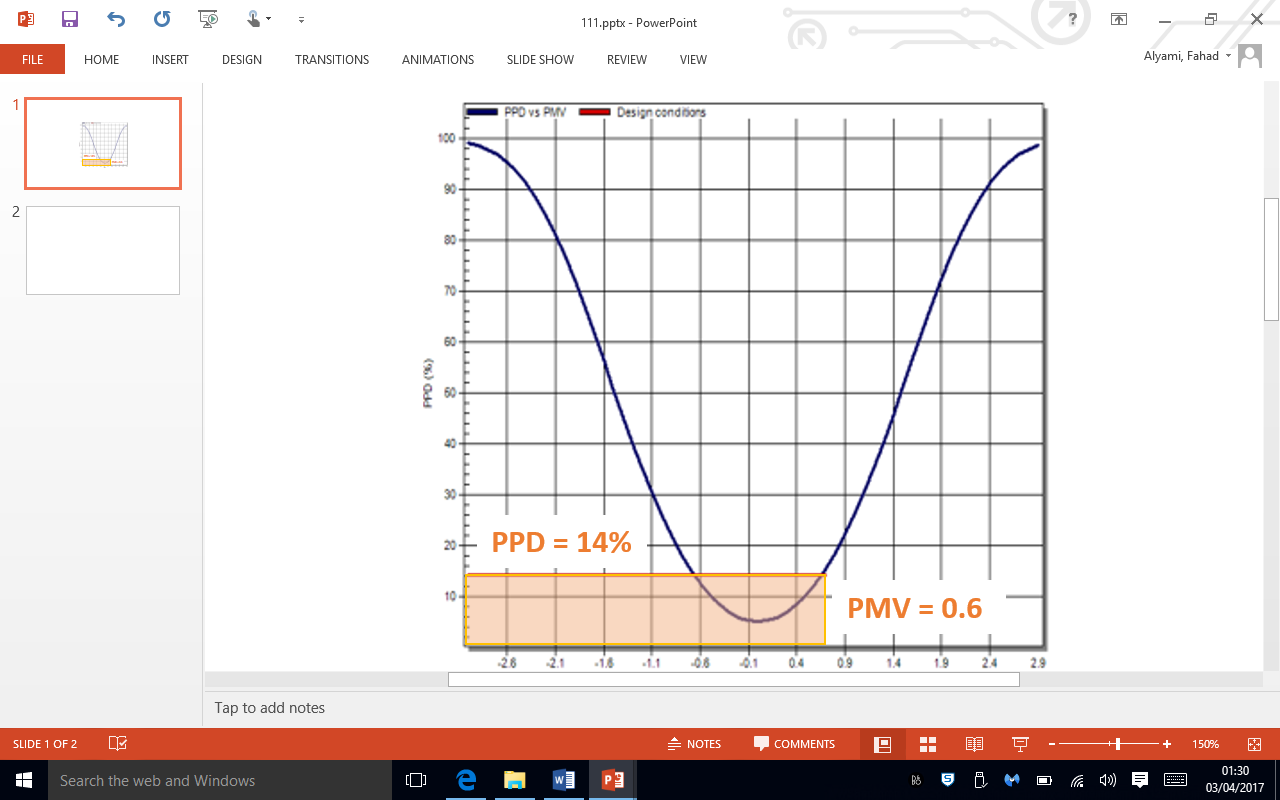
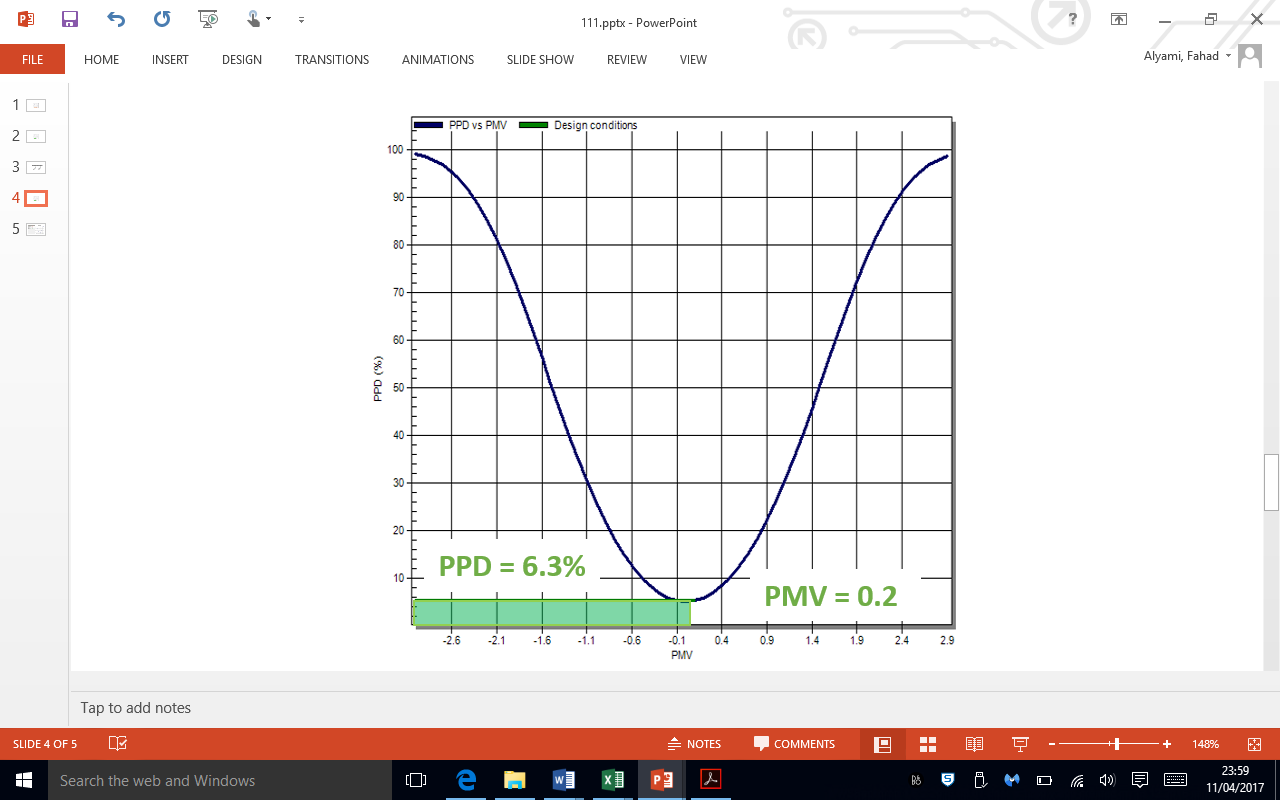


Figure 3. Cross section through the used walls in this paper while (A): existing office construction combination, base case and (B) is developed case with insulation.

Figure 4 shows the hourly internal air temperatures in the modelled office for the existing office and the insulated office over a 12 hour period. It can be seen that throughtout the working day the base case façade would always create a warmer temperature in the office compared to the insulated office. There is a small but consistent difference in temperatures for the two envelope designs, and because these differences exist over many hours then this would be reflected as differences in the cooling energy required. Over an entire summer, the additional cooling energy consumed by the base case office would become noticeable.

Figure 4. Modelled hourly average air temperatures for the existing office construction and the insulated office.

Based on the predicted environmental conditions and assumed clothing and activity levels of the office workers, it was possible for *Designbuilder®5.0* to calculate the PMV and PPD values for the existing and insulated office set-ups. Figure 5 shows the results of the thermal comfort analysis. Adding the insulation to the office’s envelope improved thermal comfort, with the PMV for the existing office moving from +0.6 (which is outside the ANSI-ASHRAE Standard 55 comfort range of -0.5 and +0.5) to a PMV of +0.2 when the insulation was in place.

**Wall B**

**Insulated Case**

**Wall A**

**Base Case**

1. (B)

Figure 5. Thermal comfort graph for (A) existing office and (B) insulated office.

***Parametric analysis for glazing choice***

Fenestration is another key factor in envelope performance analysis for a hot arid climate, and so a second study examined the impact of replacing 6mm thick single glazing in the base case office with good quality double glazing consisting of two 6mm panes and a 13mm thick, argon-filled spacing (see Figure 6).

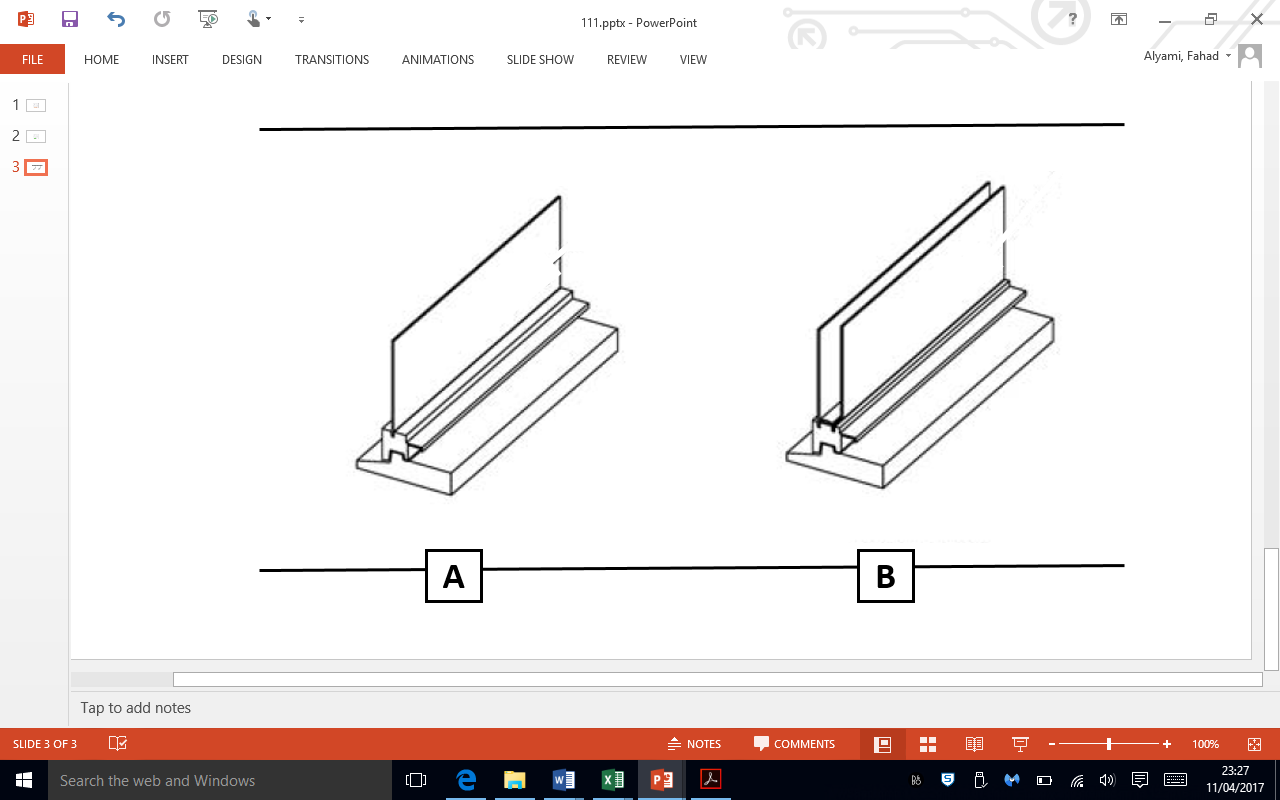
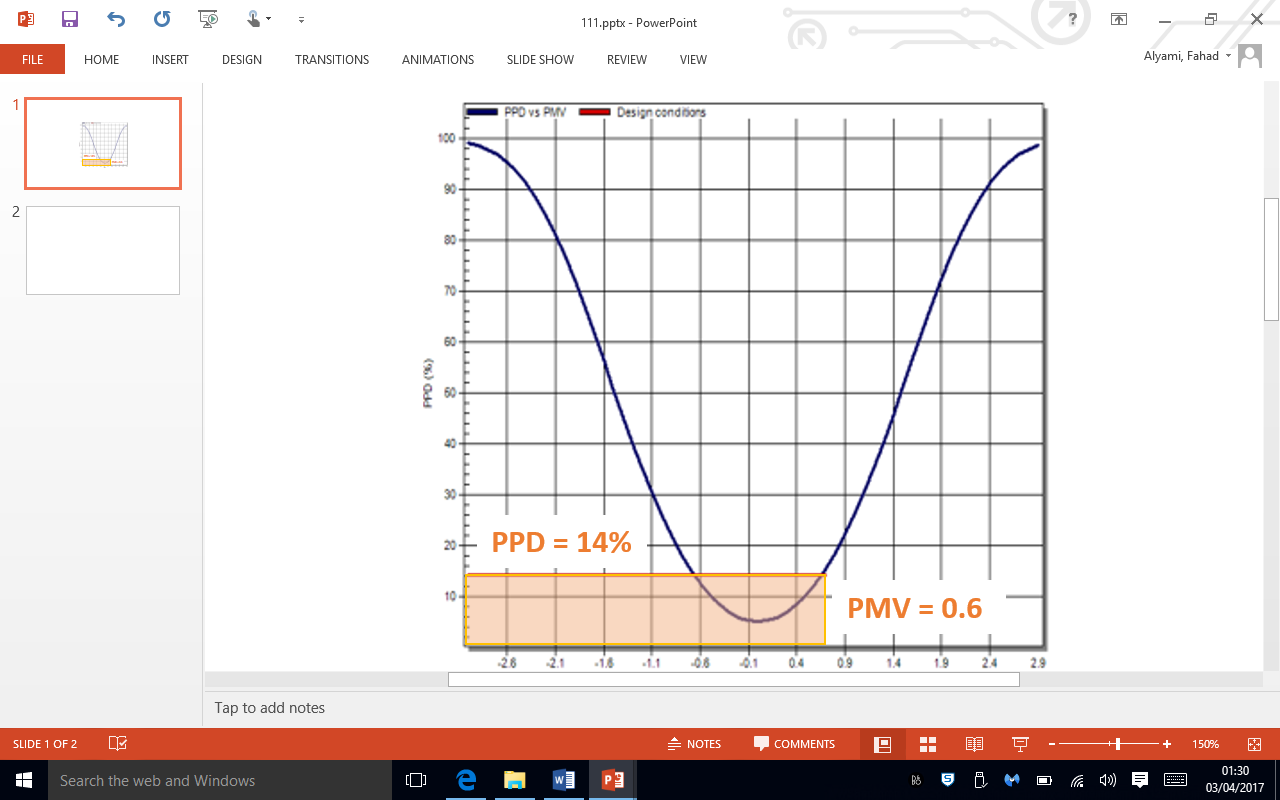
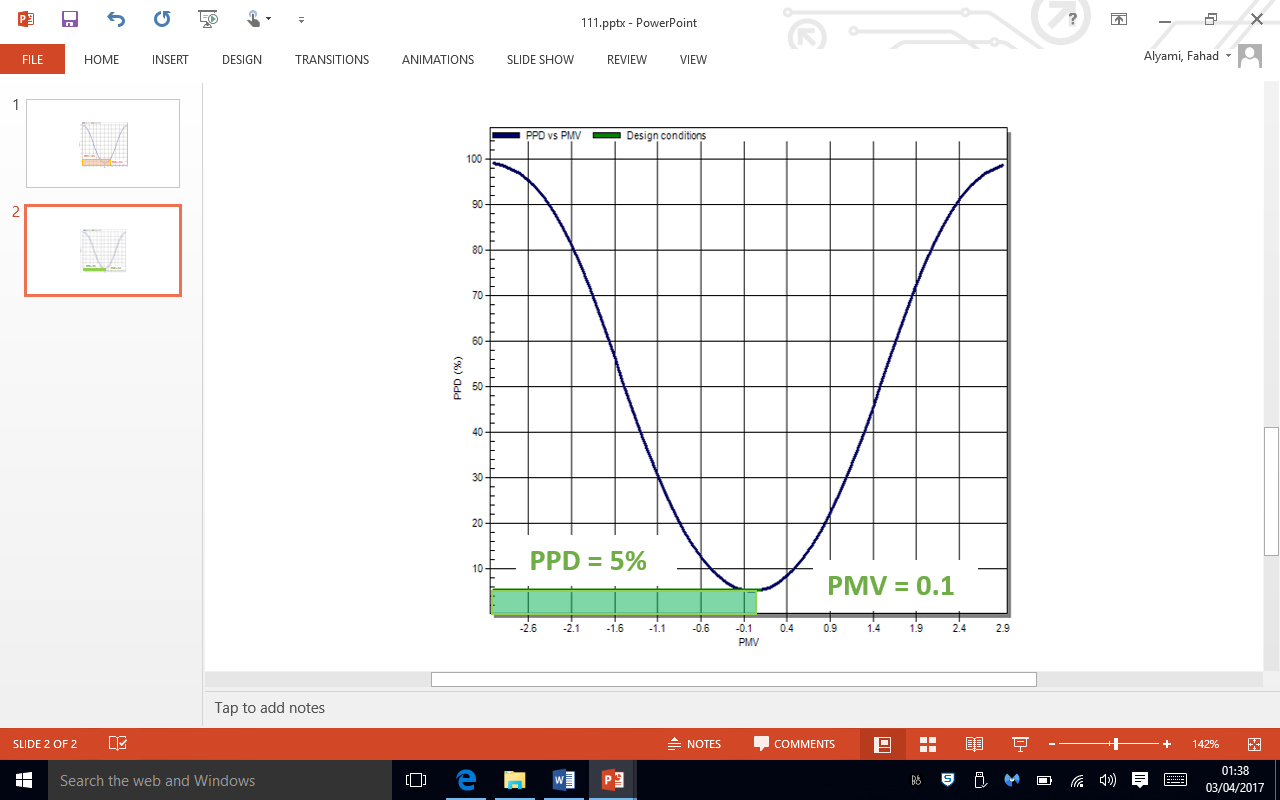


Figure 6. Isometric illustration of the glazing used in this paper, where window (A) is the single clear glazing, base case and (B) ‎is the developed case with double glazing and argon fill between the panes.‎

Figure 7 shows the hourly internal air temperatures in the modelled office for the existing base case office and for the office with the higher specification glazing over a 12 hour period. It can be seen that base case glazing (A) would increase internal temperatures by 1-1.5% compared to the double glazed office (B). Over a long cooling season these small differences in temperature would be evident in terms of higher cooling energy costs for the base case office.

Figure 7. Modelled hourly average air temperatures for the existing office glazing and the office with the higher specification glazing.

Figure 8 shows the results of the thermal comfort analysis for the new glazing. Changing the glazing for the office’s envelope improved thermal comfort, with the PMV for the existing office moving from 0.6 to a PMV of 0.1 when the treated glazing was in place.

**Window A**

**Base Case**

**Window B**

**Dbl. Glazed Case**

Figure 8. Thermal comfort graph for (A) existing office and (B) improved glazing office.

**Discussion and Conclusion**

This paper describes initial findings from a larger study that is investigating a range of passive envelope interventions to reduce cooling loads and improve thermal comfort in high-rise office buildings in Saudi Arabia, both for current and future climatic conditions. These preliminary results highlight that even simple passive changes to envelope design can be effective, even in the very demanding hot arid conditions of a country such as Saudi Arabia.

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