Application of analytical hierarchy process for selecting an interior window blind

Window blinds have a substantial role in shaping the energy consumption and improving thermal comfort and visual comfort. However, difficulties in selecting a window blind remain, due to existence of potential conflicts between visual, thermal, energy and life cycle cost. To overcome this problem, this study evaluates the performance of interior blinds, including venetian with slat of 0° and 45°, roller and double pleated blinds with respect to visual, thermal, energy and life cycle cost. Later, the Analytical hierarchy method (AHP) is used for selecting the best blind based on trade-off among the visual, thermal, energy and life cycle cost. In using AHP, visual comfort is determined as most important objective with a weight of 52%. The results show that venetian blind with slat of 0° drawn 100% is the trade-off blind. Accomplishing the sensitivity analysis on blinds' global weight shows that venetian blind with slat of 0° drawn 100% remains the trade-off blind until the weight of energy and life cycle cost is below 37% and 57% respectively and the weight of visual comfort is above 4%. However, changing thermal comfort weight has no impact on ranking of the blinds. This study shows the capability of AHP in managing the conflicts.

Keywords: Interior window blinds, Analytical hierarchy process, Energy consumption, Life cycle cost, Thermal comfort, Visual comfort

Introduction

In Sweden, the final energy consumption in building sector was around 144 TWh/year in 2013 (Swedish energy agancy, 2015), which corresponds to 7% of total carbon dioxide emissions in this country at the same year (Swedish Environmental Protection Agency, 2015). However, due to increased environmental concerns across the world and great potential of building sector in decreasing the greenhouse gas emissions with lowest cost (Rahmani Asl, Stoupine, Zarrinmehr and Yan, 2015), the architects and building experts try to improve the energy performance of buildings (Rahmani Asl et al., 2015). In this context, windows gain increasing importance in shaping the energy performance of a buildings (Nikoofard, Ugursal and Beausoleil-Morrison, 2014). Windows can reduce the heat demand during the cold seasons by penetrating solar heat, but they are also the main source of heat loss through transmission (Avasoo, 2007), and in warm seasons they can add on to the total cooling demand in buildings or be a major source of overheating in free-running buildings. Furthermore, windows have important role in determining occupants' visual comfort. According to Mangkuto, Rohmah and Asri (2016), improving visual comfort usually translates to enlarged window area for increasing daylight penetration and having a better view. The benefits of providing daylight and view have been studied in association with promoted health and productivity (Heerwagen, 1998), (Veitch, 2001). However excessive amount of daylight, penetrated through larger windows, increase the glare risk. Furthermore, they may diminish occupants' privacy. In this context, designing and selecting a proper window blind can largely help in increasing the visual comfort inside an indoor environment and provides privacy to occupants without increasing too much the energy need for space heating during winter.

Mainly, there are three groups of blinds: interior, between glazing and exterior ones. Interior blinds have insignificant effect on reducing energy need, because they intercept solar radiation after it penetrates into indoor environment (Hoffmann and Lee, 2015). The main purpose of interior blinds is indeed to reduce daylight penetration and decreasing glare risk (Hoffmann et al., 2015). Controlling glare in countries such as Sweden can be difficult due to large variation in solar elevation angle and solar intensity between summer and winter (Bülow-Hübe, 2007); (Dubois, 2001). This problem highlights the importance of having interior blinds in this country.

In general, interior blinds can be designed either movable or fixed, and movable blinds can be operated manually and/or automatically. The movable blinds (Nikoofard et al., 2014), especially those with automatic control (Kim, Park, Yeo and Kim, 2009), have better performance considering energy consumption because they improve the interior thermal condition and occupants will have less need to repeatedly adjust the air temperature set-point (Bessoudo, Tzempelikos, Athienitis and Zmeureanu, 2010). Furthermore, the results by Chan and Tzempelikos (2013) and Yun, Yoon and Kim (2014) indicate that interior blinds with automatic control system improve the interior visual comfort.

The main concern in designing an automatic controlled blind for improving energy performance, visual comfort and thermal comfort is to configure the blind in either open loop or closed-loop system. An open-loop system uses a sensor that monitors the incoming solar incident radiation, but not the output, for instance whether or not the work plane illuminance meets the desired requirement (O'Brien, Kapsis and Athienitis, 2013). In contrast, a closed-loop system utilizes a sensor which monitors the output's condition and adjusts the position of a blind to attain the desired requirement. According to O'Brien et al. (2013), closed-loop is more advantageous than open-loop control system since the obtained results of analysing light and thermal conditions are more accurate.

Despite the closed-loop automatically controlled blinds present multiple benefits in improving light and thermal conditions, using this kind of blinds may increase the initial cost (O'Brien et al., 2013) and maintenance cost (Nikoofard et al., 2014). Moreover, the performance of automatically control blinds is highly dependent on blinds' specifications, including reflectance, absorption, and light and solar transmittance of blinds' material. Hence, at the presence of these conflicts, difficulties in designing blinds with closed-loop automatic control system and selecting a suitable one still remain.

The available simulation programmes such as EnergyPlus (Lawrence Berkeley National Laboratory, 2016), IDA ICE (IDAICE, 2016), Diva for Rhino (Diva4Rhino, 2016), Grasshopper (Grasshopper, 2016) and COMFEN (Lawrence Berkeley National Laboratory, 2016) can calculate the effect of various blinds on visual comfort, thermal comfort, energy consumption and cost separately. Even if these programmes are affected by some limitations, they can support the selection of an interior blind based on an individual criterion, but not on multiple criteria, where there is likely to have a trade-off between the criteria. According to Monghasemi, Nikoo, Fasaee and Adamowski (2015), it is not recommended to make a decision relying on a single criterion. In this context, a multi-criteria decision making (MCDM) method helps to achieve a trade-off solution between meeting occupants' preferences for visual comfort and thermal comfort and reducing cost and energy consumption. MCDM is prevalent in building design (Monghasemi et al., 2015), but it has not been utilized in designing window blinds. Hence, this study aims to apply the MCDM method in designing window blinds by analysing the performance of four different types of automatically controlled interior blinds with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Later, considering the gathered information, it aims to select the best blind based on the trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost. This process is accomplished by using the Analytical Hierarchy Process (AHP) as AHP is the most utilized MCDM method due to its flexibility and simplicity (Jato-Espino, Castillo-Lopez, Rodriguez-Hernandez and Canteras-Jordana, 2014). AHP ranks the blinds considering their performance and introduces the best trade- off blind.

Methodology

This study investigates the performance of the interior window blinds prevalently-installed in Sweden such as roller blinds, double pleated blinds, and two types of venetian blinds where the slat of the louvers is 0° (closed venetian blind) and 45° (semi- closed venetian blind) (Fig. 1 and Fig. 2). This decision was made, because visual performance of a venetian blind is gradually changing by decreasing the slat of louvers (Mahdavinejad and Mohammadi, 2016). Venetian blinds with lower slat of louvers are more effective in controlling glare risk (Mahdavinejad et al., 2016). Since, controlling glare in Sweden is a difficult task (Bülow-Hübe, 2007); (Dubois, 2001), this study analyses two venetian blinds where the slat of the louvers is 0° and 45° as lower and upper margins.

The height of blinds was changed from 10 % to 100 % of window's height in 10 % intervals. This decision was made to determine whether or not a small blind has a positive effect in cutting the investment cost. The combination of four blinds with ten different heights generates 40 different blind alternatives.

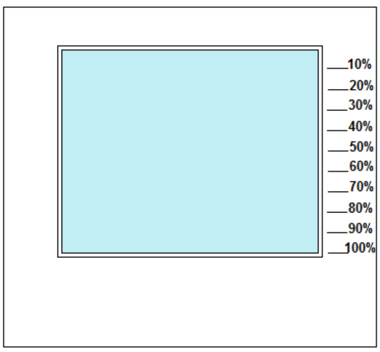

Figure 1. Length of drawn blind

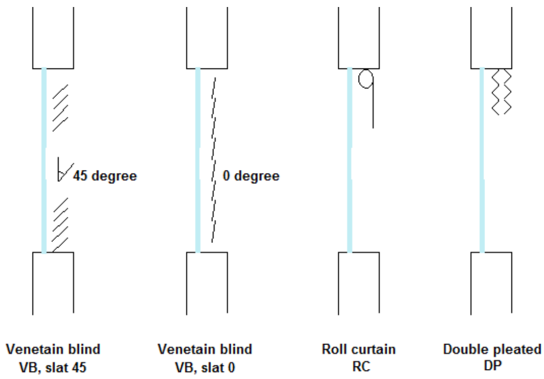

Figure 2. Investigated blinds

Visual comfort evaluations

The performance of each blind considering visual comfort was studied by Rhinocore (Rhino3d, 2016) and Diva for Rhino plugin. Rhinocore is a 3D graphic software, which allows to develop 3D models for further analyses (Rhino3d, 2016) . Diva for Rhino is a plugin for Rhinocore program, which enables to accomplish a series of visual comfort evaluations (Diva4Rhino, 2016). Visual comfort evaluations were started by developing a 3D model of an office building located in Gothenburg, Sweden. The 3D model was developed in Rhinocore and comprised other neighbouring areas including a parking area and a lake in south- east direction. However, the performance of the blinds was studied in a single office room located on the first floor. The 3D model of the office room was developed further by adding interior office accessories including a desk, a chair and a desktop. Fig. 3 shows the section and plan layout of the room. Following the recommendations of Light and Room Standard (in Swedish: Ljus och Rum), the reflectance of inner surfaces, including walls, ceiling and floor were considered as 60%, 80% and 20%, respectively, (Månsson and Schönbeck, 2003).The office room equipped with triple glazing window, which oriented north- east direction. The glazing system consists of three 4 mm-thick glasses with 16 mm-air gap between each pair of glasses. The interior gap is filled with 10% air and 90% argon, while the exterior one is filled with 100% air. The interior glass is laminated with low-emission coating (Elitfonster, 2016). The mentioned 40 blinds were modelled in Rhinocore as separated 3D layers. During the simulations, only one layer at a time was activated while the rest of layers were turned off. This process helped to evaluate the performance of all 40 blinds while only one 3D model was developed for the office room.

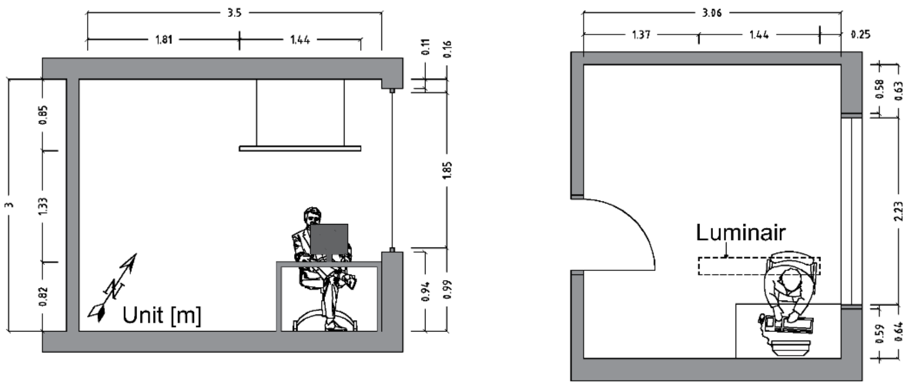

Figure 3. Section and plan layout of the office

Table 1 presents the simulation layouts of the blinds. Furthermore, a pendant luminaire present in the office room was modelled at 2.15 m from the floor level. The luminaire consisted of two 35W florescent lamps that could be controlled by a simple switch on/ off bottom.

Table 1. Simulation layout

	Specification	Value	Description
Venetian blind*	Visible transmittance	0%	
	Slat width	0.05 m	
	Slat separation	0.04 m	
	Slat angle	0° and 45°	
	Visible light reflectance from louver	70%	
Double pleated*	Diffuse transmittance	0%	Fabric treats as totally opaque material
	Openness factor	3%	
	Visible light reflectance of surface	55%	
	Roughness	0	
	Specular reflectance	0	Represents a diffuse surface
Roller blind*	Diffuse transmittance	0%	Fabric treats as totally opaque material
	Openness factor	3%	
	Visible light reflectance of surface	70%	
	Roughness	0	
	Specular reflectance	0	Represents a diffuse surface
Work plane	Work plane illuminance	500 lx	Minimum amount of light available on the work plane at a height of 0.82 m

* Specifications of the blinds were collected from a company in Sweden.

When the 3D models were developed, Diva for Rhino plugin was employed for analysing the performance of the blinds by calculating mean daylight autonomy (DA) and discomfort glare probability (DGP). DA is the percentage of the annual occupied hours that a minimum illuminance threshold (500 lx) is reached by only daylight (Carlucci, Causone, De Rosa and Pagliano, 2015a). The illuminance threshold of 500 lx is considered as the minimum daylight amount for performing office tasks. Due to the ability of DA in considering real weather conditions and presenting the amount of light over a long period of time, this metric was appreciated in visual comfort evaluations. DGP is a metric for assessing the glare status in an environment. This metric evaluates the perceived illuminance level by an observer and consequently has sufficient correlation with glare perception (Carlucci et al., 2015a). A higher DGP corresponds to a higher glare risk in the analysed room.

Furthermore, the daylight uniformity was calculated for all blinds. Uniformity describes if daylight spreads evenly over the work plane (Carlucci et al., 2015a). DA, DGP and uniformity was obtained while a closed-loop automatic control based on state of glare has been defined for each blind.

Energy and thermal comfort evaluations

The performance of the blinds considering energy consumption and thermal comfort was studied in IDA ICE program. IDA ICE is a dynamic simulation program, which is widely used to study the energy and thermal performance of a room and/or building in Sweden (IDAICE, 2016). A 3D model of an office room was built in IDA ICE program. The office room had the same specifications as mentioned above. The room was located at the intermediate level (bounded between two other floors), the façade equipped with the window is an external wall, while the others are adiabatic.

The dimensions and specifications of each blind was defined and saved separately, which means that 40 IDA ICE simulation files, each representing one single blind, were generated. Table 2 presents the heating, ventilation and air conditioning (HVAC), occupancy and thermal characteristics of the office room. In order to set a similar blind control in IDA ICE, the detailed dynamic blind timetable (timetable for dynamic control of blinds) produced by Diva for Rhino plugin was utilized.

Table 2. Characteristics of the single office

General properties	**Values or models**
Occupancy time	7:00 am to 6:00 pm
Activity level	1.2 met
Clothing resistance	0.5 clo in summer and 1 in winter
U-value of external walls	0.54 W/ (m^2 K)
U-value of internal walls	0.61 W/ (m^2 K)
U- value of the window	1.1 W/ (m^2 K)
Air flow rate	0.35 l/ (s m^2)
Efficiency of fan for ventilation	0.6
Air tightness	0.1 ACH
Heating system	District heating with efficiency equal to 1. Energy system is ideal and all the efficiencies of subsystems are hence equal to unity.
Cooling system	District cooling with efficiency equal to 1. Energy system is ideal and all the efficiencies of subsystems are hence equal to unity.

Regarding energy consumption, the annual electricity demand for lighting, and annual energy need for space heating and cooling were calculated for each of the 40 room configurations. However, the obtained electricity demand for lighting was similar for all blinds, because luminaire was assumed to be controlled by a simple switch on/off bottom.

Operative temperature and predicted percentage of dissatisfied (PPD), the two widely used metrics for thermal comfort evaluations (Linden, Loomans and Hensen, 2008), were obtained from IDA ICE. In performing thermal comfort evaluation, office activity of 1.2 met and clothing resistance of 0.5 clo in summer and 1 clo in winter were considered (ISO7730-Standard, 2005). For the analyses presented hereby, due to the very low air speed registered in the model, operative temperature can be calculated as the average of the mean radiant and air temperature (Chandel and Aggarwal, 2012). PPD, as a metric for evaluating Fanger's thermal comfort model, calculates the percentage of occupants who are likely dissatisfied with thermal conditions to which they are exposed (García, 2010).

Life cycle cost evaluations

The Life cycle cost analysis for each blind was made in excel by calculating the present value per 1 m² of room area (Eq. 1). In calculation of present value, a 10 year-period life span (2015-2025) and 6% interest rate was considered for each blind. However, the cost of annual energy use in Eq.1 was obtained considering only district heating and cooling demands as the electricity demand for electric lighting was similar among all 40 blind configurations. Furthermore, it was assumed that the energy price for district heating and cooling will increase by 9% per year, which was the average inflation rate between 2005 to 2011 in Gothenburg (GothenburgEnergy, 2015).

$$K_n = \sum_{t=0}^{n}(D_t + U_t) * \frac{1}{(1+r)^t} + I_0 \quad (1)$$

$$D_t = E * \alpha(1+\beta)^t \quad (2)$$

Where;

K_n is present value during lifespan of n year;

U_t is annual maintenance cost;

D_t is annual energy consumption cost;

r: interest rate

t: lifespan of n years

E is annual energy consumption (kWh/m²)

α is energy price per kwh/m²

β is inflation in energy price (%)

I_0 is the investment cost

The life cycle cost analysis includes; i) the initial investment cost of the blind which was collected from a company catalogue in Sweden and was calculated considering the size of each blind; ii) the cost of energy used during the life span of the blind which was determined according to the presented results for annual district heating and cooling by the IDA ICE program and iii) the annual maintenance cost which was collected from a company in Sweden and assumed to be the same for all design alternatives.

Analytical hierarchy process

The Analytical hierarchy process (AHP) is widely utilized MCDM method in achieving a trade-off solution in different fields such as indoor environment quality (Lai and Yik, 2009), passive design (Chong and Shyang, 2014), sustainability (Markelj, Kitek Kuzman, Grošelj and Zbašnik-Senegačnik, 2014); (Bhatt, Macwan, Bhatt and Patel, 2010); (Wong and Li, 2008); (Chandratilake and Dias, 2013); (Alwaer and Clements-Croome, 2010), and daylight performance (Arpacioglu and Ersoy, 2013).

According to Podgórski (2015), AHP method is implemented following these steps:

1) decomposing the MCDM problem into several levels, including goal, objectives, their respective criteria and solutions. This process creates a hierarchy model. Fig. 4 shows a schematic hierarchy model for three objectives and three solutions (see section 2.4.2 for example);
2) performing pairwise comparisons among objectives stated in the hierarchy model and their criteria, also obtaining the weight vector for each criterion. The pairwise comparisons should be conducted following the presented numerical ratings presented in table 3;
3) performing pairwise comparison between the solutions in relation to each criteria and obtaining the weight vector for the solutions;
4) determining the global weight vector for each solution and ranking them for achieving a trade- off solution. The solution with highest global weight is known as the trade-off solution.

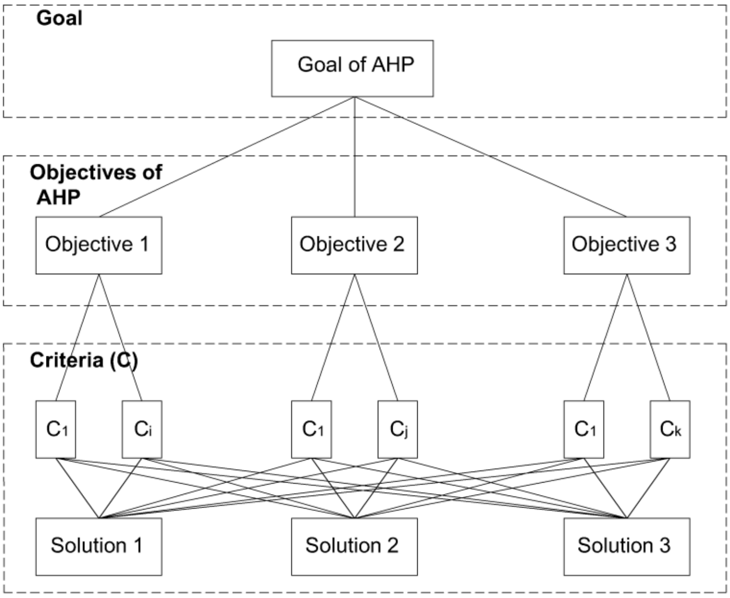

Figure 4. Schematic illustration of AHP hierarchy model

Table 3. Pairwise numerical rating (Saaty, 2008)

AHP, Relative importance		Numeric rating
Equal importance	Two criteria contribute equally to the objective	1
Somewhat more important	Experience and judgment slightly favour one over the other	3
Much more important	Experience and judgment strongly favour one over the other	5
Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice	7
Absolutely more important	The evidence favouring one over the other is of the highest possible validity	9
Intermediate values	When compromise is needed	2,4,6,8

Performing pairwise comparisons between objectives and criteria in step 2 generates comparison matrices. Matrix A shows the developed comparison matrix among criteria.

$$A = \begin{array}{c} \\ \text{Criteria 1} \\ \text{Criteria 2} \\ \text{Criteria 3} \\ \text{Criteria 4} \end{array} \begin{array}{c} \begin{array}{cccc} \text{Criteria 1} & \text{Criteria 2} & \text{Criteria 3} & \text{Criteria 4} \end{array} \\ \begin{bmatrix} 1 & a_{1,2} & \dots & a_{1,n} \\ 1/a_{1,2} & 1 & \dots & a_{2,n} \\ \dots & \dots & 1 & \dots \\ 1/a_{1,n} & a_{n,2} & \dots & 1 \end{bmatrix} \end{array}$$

Where $\boldsymbol{a_{i,j}}$ means that criteria i being compared to criteria j. On the diagonal of the matrix, $\boldsymbol{a_{i,j}}$ is equal to 1 since i = j. When the comparison matrix is developed, the weight of each criterion in step 2 can be calculated by:

- Calculating the sum of each column in the matrix ($\sum \boldsymbol{a_j}$).
- Dividing each $\boldsymbol{a_{i,j}}$ in column *j* by the calculated $\sum \boldsymbol{a_j}$ in previous step (normalization of the matrix).

- Obtaining the average of each row in normalized matrix ($\overline{a'_i}$). a'_i represents the weight of a criteria or solution in row *i*.

In step 3, a comparison matrix should also be developed by comparing the solutions in relation to each criterion (matrix B). The weight calculation process is similar to step 2.

$$B= \begin{array}{c} \text{Solution 1} \\ \text{Solution 2} \\ \text{Solution 3} \\ \text{Solution 4} \end{array} \overset{\begin{array}{cccc} \text{Solution 1} & \text{Solution 2} & \text{Solution 3} & \text{Solution 4} \end{array}}{\begin{bmatrix} 1 & a_{1,2} & \dots & a_{1,n} \\ 1/a_{1,2} & 1 & \dots & a_{2,n} \\ \dots & \dots & 1 & \dots \\ 1/a_{1,n} & a_{n,2} & \dots & 1 \end{bmatrix}}$$

When the weights of the solutions and criteria were achieved, the global weight of each solution in step 4 can be obtained. The global weight is the sum of products of the weight of a given solution and weights of the criteria. For instance, if $\boldsymbol{W_{s,1}}$ is the weight of the first solution and $\boldsymbol{W_{c,i}}$ is the weight of the criteria *i*, then the global weight of the first solution is:

$$\textbf{Global weight of solution 1 } (\boldsymbol{GW_1}) = \sum_{\mathbf{i=1}}^{\mathbf{i=n}} \mathbf{W_{s,1}} \times \mathbf{W_{c,i}} \tag{3}$$

One of the most significant elements of AHP method is the calculation of consistency ratio (CR). CR detects whether or not the applied pairwise comparisons, are consistent. According to Ordouei, Elkamel, Dusseault and Alhajri (2015), CR should be smaller than 0.1 and 0.08 for matrices with $n > 3$ and $n = 3$ respectively. The CR is calculated following Eq.4 and Eq.5.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

$\boldsymbol{\lambda_{max}}$ is the maximum eigenvalue of the developed matrices in step 2 and 3. $\boldsymbol{\lambda_{max}}$ for developed matrix A is calculated follow Eq. 6.

$$\boldsymbol{\lambda_{\max}} = \sum \mathbf{a_1} \times \overline{\mathbf{a'_1}} + \sum \mathbf{a_2} \times \overline{\mathbf{a'_2}} + \dots \tag{6}$$

RI or the random consistency index in eq. 5 is a reciprocal matrix (Hotman, 2005). The average RI of criteria size $n = 10$ is shown in Table 4.

Table 4. Random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

According to Leonelli (2012), since global weights are obtained by performing qualitative pairwise comparison, it is necessary to control the sensitivity of the results. Performing this kind of analyses helps to make an informed decision (Leonelli, 2012). Sensitivity test evaluates the variation of global weights with respect to change in criteria's weight (criteria' weight can be changed by changing the pairwise comparisons). In this process, the global weight of an alternative is expressed as a linear function of the criteria weight (Leonelli, 2012). The linear function can be developed using equation 7.

$$(\boldsymbol{GW}_i) = \frac{GW_i'' - GW_i'}{W_{c,j}^{"} - W_{c,j}'} \times \left(W_{c,j} - W_{c,j}'\right) + (\mathrm{GW}_i') \quad (7)$$

Where

GW_i is the global weight of *i*th solution when the weight of *j*th criteria is $W_{c,i}$

GW_i' is the global weight of *i*th solution when the weight of *j*th criteria is changed to $W_{c,j}'$

GW_i'' is the global weight of *i*th solution when the weight of *j*th criteria is changed to $W_{c,j}^{"}$

GW_i and $W_{c,i}$ are obtained following four steps, described above. $W_{c,j}'$ can be calculated by changing the pairwise comparisons in matrix A. Later, GW_i' should be obtained based on $W_{c,j}'$ and using equation 3. In using equation 7, only two iterations are required to develop linear function between global weight and criteria weight (Leonelli, 2012). However, the accuracy of the linear function can be tested by calculating $W_{c,j}^{"}$ and GW_i'' and testing whether or not it lies on the linear function.

Use of AHP in blind selection

In this study, the AHP method was employed using MakeitRational program (MakeitRational, 2016) due to its simplicity in developing a hierarchy model and performing pairwise comparisons. MakeitRational is an online program which has been designed for implementing AHP method. The eligibility of this program has been discussed and found appropriate by other studies (Sabharwall, Kim, McKellar, Anderson and Patterson, 2011); (Ishizaka and Nemery, 2013). Fig. 5 shows the developed hierarchy model in the MakeitRational program. As seen in this figure, the goal of the AHP is to select the best blind among forty blinds based on trade-off between visual comfort, thermal comfort, energy consumption and life cycle cost. Moreover, the objectives of the hierarchy model and their respective criteria were specified in the hierarchy model.

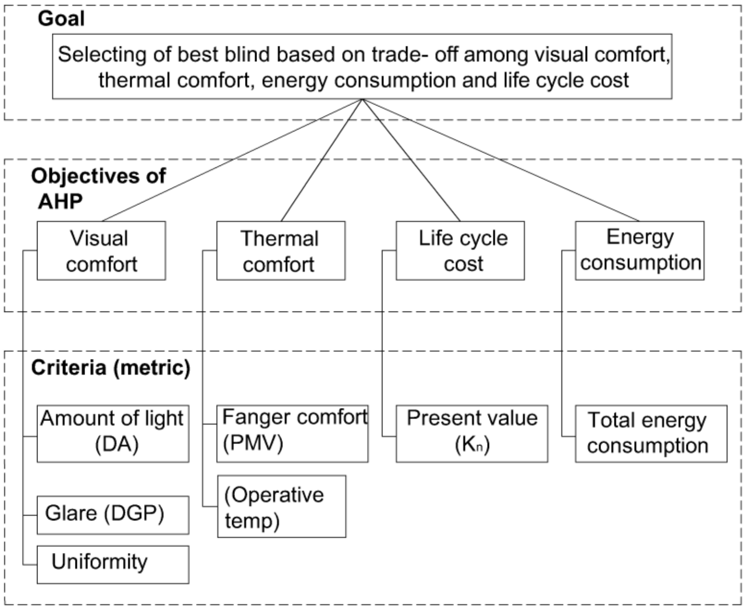

Figure 5. Developed hierarchy model in MakeitRational program**.**

When the hierarchy model was developed, a series of pairwise comparisons as shown in matrix C were performed among the visual comfort, thermal comfort, energy consumption and life cycle cost. The relative importance among these objectives was retrieved from previous studies. The pairwise comparisons between visual comfort, thermal comfort and energy consumption were performed based on presented results by Kats, Alevantis, Mills and Perlman (2003). According to them, improving visual comfort and thermal comfort presents approximately seven times more economic benefits than energy consumption. Comparisons between the visual comfort and thermal comfort follows the results presented by Frontczak, Andersen and Wargocki (2012). They analysed occupants' satisfaction with the overall indoor environment in correlation with their satisfaction with visual comfort, thermal comfort, air quality and acoustic. The correlation was studied by obtaining Spearman correlation coefficient. Comparing the coefficient values shows that visual comfort has slightly more effect than the thermal comfort on occupants' satisfaction of the overall indoor environment.

The calculated CR for matrix C is about 0.033 (smaller than 1), which means the applied pairwise comparisons are consistent to calculate the weight of each blind.

C=

	Visual comfort	Thermal comfort	Energy consumption	Life cycle cost	Weight
Visual comfort	1	2	7	7	0.52
Thermal comfort	1/2	1	7	7	0.36
Energy consumption	1/7	1/7	1	1	0.06
Life cycle cost	1/7	1/7	1	1	0.06

Pairwise comparisons among visual comfort criteria were also performed by conducting literature study. According to Chung and Ng (2016), the amount of light (DA in this study) is more important than glare (DGP in this study) in a small degree. Furthermore, it is slightly more important than daylight uniformity (Chung et al., 2016). Matrix D presents the applied comparisons between visual comfort criteria. The calculated CR for matrix D is about 0.01 which shows the consistency of applied pairwise comparisons.

D=

	Amount of light	Glare	Uniformity	Weight
Amount of light	1	2	3	0.54
Glare	1/2	1	2	0.3
Uniformity	1/3	1/2	1	0.16

However, in developing the comparison matrix for thermal comfort criteria, since operative temperature and PPD evaluate the thermal conditions in relation to occupants' satisfaction (Linden et al., 2008), it was assumed that operative temperature has equal importance in relation to PPD. Thus the calculated CR for matrix E was equal to zero.

E=

	Operative temperature	PPD	Weight
Operative temperature	1	1	0.5
PPD	1	1	0.5

The pairwise comparisons between energy performance criteria were accomplished by comparing the average demands for district heating, district cooling and the electricity demand for lighting. The average district heating and cooling demands were 82.2 kWh/ (m^2 year) and 26 kWh/ (m^2 year) respectively. The electricity demand for lighting was 11.6 kWh/ (m^2 year) for each blind configuration. The calculated CR was about 0.004 which shows the pairwise comparisons in matrix F are consistent.

F=

	Heating demand	Cooling demand	Electricity for lighting	Weight
Heating demand	1	3	6	0.67
Cooling demand	1/3	1	2	0.22
Electricity for lighting	1/6	1/2	1	0.122

Considering life cycle cost, only present value has been calculated for evaluating the performance of the blinds.

Results

Fig 6 illustrates the global weight of each blind calculated by MakeitRational program. As seen in this figure, the venetian blind with slat 0° and drawn 100% (VB slat 0°, 100%), roller blind drawn 100% (R, 100%) and double pleated blind drawn 100% (DP, 100%) gained the highest global weight among other blinds. This occurs due to strength of these blinds in reducing significantly the glare risk and improving visual comfort (amount of light and uniformity). In this context, visual comfort which was identified as the most important objective in matrix C, plays a greater role in achieving a higher global weight than other objectives. Accordingly, the global weight of VB slat 0°, 100%, R, 100% and DP, 100% are significantly larger than the global weight of other blinds.

The variance in the global weights of other blinds is very small due to similarity of their performance. Considering thermal comfort, interior blinds intercept solar radiation after it penetrates into indoor environment through windows, hence they have insignificant effect on thermal comfort. PPD was 9% for all blinds configurations while operative temperature changed about 0.1 C°. Regarding energy consumption, district heating and cooling demands resulted slightly changed. Variations between minimum and maximum district heating and cooling demands among forty blinds were about 1.2 kWh/ (m^2 a) and 6 kWh/ (m^2 a) respectively. That shows the sensitivity of cooling demand considering changes in blinds specification. However, electricity demand for light was constant because the luminaire was controlled by a simple switch on/ off bottom.

Regarding life cycle cost, differences in present value among the blinds had a significant influence on the global weights. In this context, investment cost had the highest influence. The investment cost for 1m^2 of the venetian blind was about 65 % and 34 % of the roller and double pleated blinds respectively. But energy consumption cost between 40 blind configurations changed slightly, since variation in district heating and cooling demands were very small. As the maintenance cost was similar among all blind configurations, venetian blind with slat 0° and drawn 100% (VB slat 0°, 100%) was found to be the best blind, due to its small investment cost in comparison with other blinds.

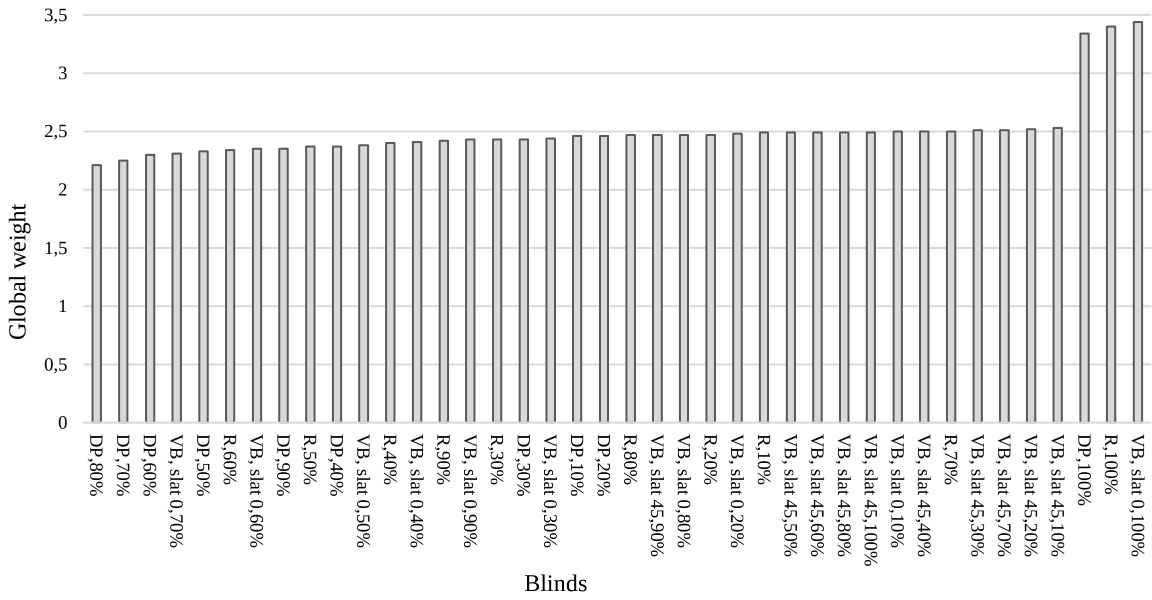

Figure 6. The global weight of each window blind

Sensitivity analysis

Sensitivity test illustrates the impact of different "what-if" scenarios on the trade-off solution. Performing sensitivity test of the global weight of blinds clarifies whether or not the VB slat 0°, 100% blind remains as the best solution if some changes are applied on the relative importance between visual comfort, thermal comfort, energy consumption and life cycle cost in matrix C. To perform sensitivity analysis, the first four blinds with highest global weights in fig. 6 were chosen. Selected blinds for sensitivity analysis consist of VB slat 0°, 100%; R, 100%; DP, 100% and VB slat 0°, 10%. The global weight of the selected blinds was recalculated once more with respect to visual comfort, thermal comfort, energy consumption and life cycle cost. Then the variation of blinds' global weight was analysed considering change in weight of visual comfort, thermal comfort, energy consumption and life cycle cost.

Fig. 7 illustrates the sensitivity of selected blinds' global weight with regard to changes in the visual comfort weight in matrix C. Considering the applied pairwise comparisons in matrix C, the weight of visual comfort was calculated as 0.52 (or 52% in Fig.7). As seen in this figure, at the current situation, VB slat 0º, 100% had the highest global weight. However, the ranking in global weight of four blinds will be changed if the visual comfort weight is below than 0.04 (4% in Fig.7). At this point, which is known as turning point, the VB slat 45°, 10% will have higher global weight than other blinds. This means that if visual comfort weight is below than 0.04, then the trade-off blind will be VB slat 45°, 10%. This occurs because having a blind down to 100% of window height increases the life cycle cost by increasing the investment cost. The investment cost of the blinds has been obtained considering their sizes. This decision was made to determine whether or not a small blind has a positive effect in cutting the investment cost.

Therefore, by reducing the weight of visual comfort (and automatically increasing the weight of thermal comfort, energy consumption and life cycle cost), blinds that have smaller investment costs will gain higher weights. As in the turning point, the priority among the blinds will change and VB, slat 45°, 10% will be the trade-off blind. The turning point in Fig. 7 is about 25.2. In calculating the turning point, global weight functions, presented by MakeitRational program were used (table 5). In other scenarios, if the current visual comfort weight is increased (greater that 52%) then the VB 0°, 100% remains as the trade- off blind. Because VB, slat 0°, 100% has better performance than other blinds in reducing the glare probability.

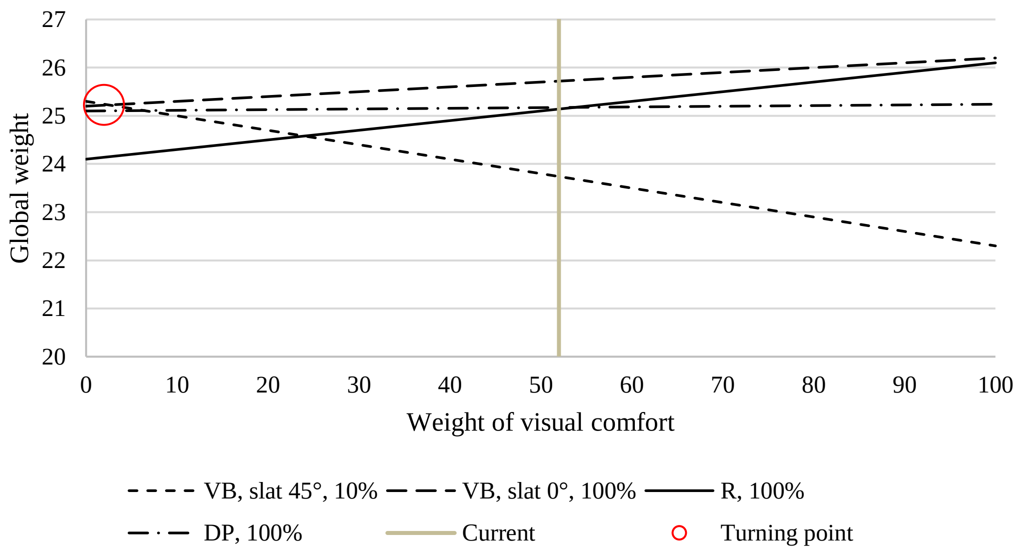

Figure 7. Sensitivity analysis with respect to visual comfort

Table 5. Sensitivity of selected blinds' global weight regarding change in visual comfort weight

Blinds	Min 0	Current	Max 100	Global weight functions
VB, slat 0°, 100%	25.20	25.72	26.20	0.01*weight of visual comfort + 25.20
DP, 100%	25.10	25.17	25.24	0.0014*weight of visual comfort + 25.10
VB, slat 45°,10%	25.30	23.74	22.30	-0.03* weight of visual comfort + 25.30
R, 100%	24.10	25.14	26.10	0.02*weight of visual comfort + 24.10

A sensitivity analysis was performed to determine the stability of ranking of four blinds considering changes in thermal comfort weight in matrix C. As illustrated in Fig. 8. increasing or reducing the weight of thermal comfort has no impact on the ranking of the blinds. This happens because interior blinds intercept solar radiation after it penetrates into indoor environment through windows. Only a small fraction of the solar radiation is then reflected, absorbed and reemitted to the internal side of the glazing hence transferred to outdoor environment. Therefore, changing the blind material or its height has no significant impact on the operative temperature and PPD. Table 6 shows the global weight function of each blind with regard to thermal comfort.

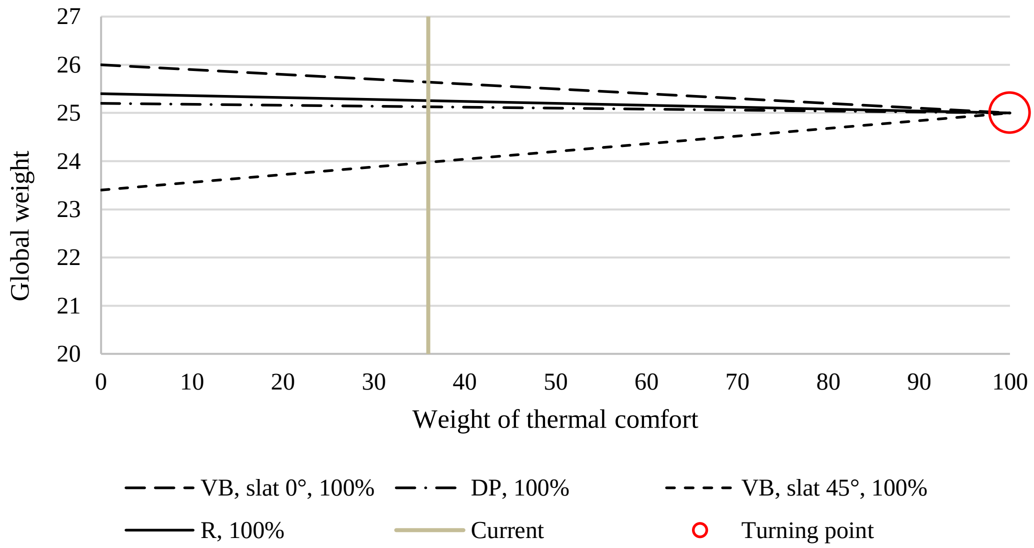

Figure. 8. Sensitivity analysis with respect to thermal comfort

Table 6. Sensitivity of selected blinds' global weight regarding change in thermal comfort weight

Blinds	Min 0	Current	Max 100	Global weight functions
VB, slat 0°, 100%	26.00	25.64	25.00	-0.01*weight of thermal comfort + 26.00
DP, 100%	25.20	25.13	25.00	-0.002*weight of thermal comfort + 25.2
VB, slat 45°,10%	23.40	23.97	25.00	0.016*weight of thermal comfort + 23.40
R, 100%	25.4	25.25	25.00	-0.004*weight of thermal comfort + 25.4

Fig. 9 and Table 7 illustrate the sensitivity of blinds global weight with regard to change the energy consumption weight. The weight of the energy consumption was calculated as 0.06 in matrix C (or 6% in Fig. 9). In the current situation, where weight of energy consumption is 0.06, VB 0° 100% is the trade-off blind as point of energy consumption. However, ranking among the blinds will be changed if the weight of energy consumption is over 0.36 (or 36.25 % in Fig.9) or turning point over 25.4. At this point, DP, 100% will have higher global weight and consequently it will be the trade-off blind. This occurs due to the ability of double pleated blinds in decreasing the U-value of the window and consequently decreasing the energy need for space heating and cooling slightly.

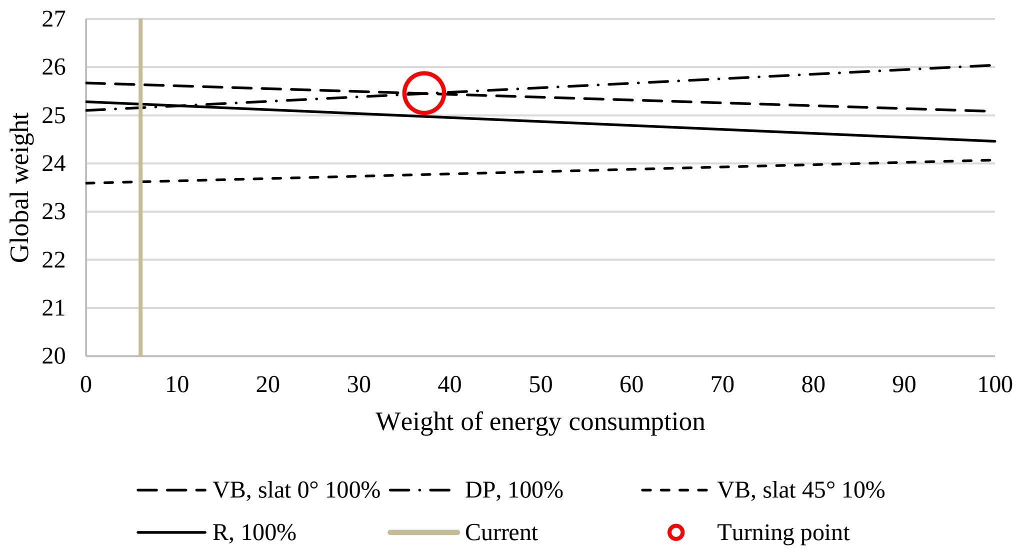

Figure 9. Sensitivity analysis with respect to energy consumption

Table 7. Sensitivity of selected blinds' global weight regarding change in energy consumption weight

Blinds	Min 0	Current	Max 100	Global weight function
VB, slat 0° 100%	25.67	25.63	25.08	-0.0059*weight of energy + 25.67
DP, 100%	25.10	25.15	26.04	0.0094*weight of energy + 25.10
VB, slat 45° 10%	23.95	23.61	24.07	0.0048*weight of energy + 23.59
R, 100%	25.28	25.23	24.46	-0.0082*weight of energy + 25.28

Fig.10 and Table 8 illustrate the sensitivity of four blinds global weight with respect to change in the life cycle cost weight. In the current situation, where weight of life cycle cost is 0.06, VB 0°, 100% is the trade-off blind. If the weight of life cycle cost is over 0.57 (or 57.05%) or over turning point at 26. 33, then VB 45°, 10% will be the trade-off blind as the point of life cycle cost. This is because by increasing the weight of the life cycle cost, blinds that are associated with smaller energy consumption, lower investment and maintenance cost will gain a higher weight. In this context VB slat 45°, 10%, which has a smaller investment cost will be the trade-off blind.

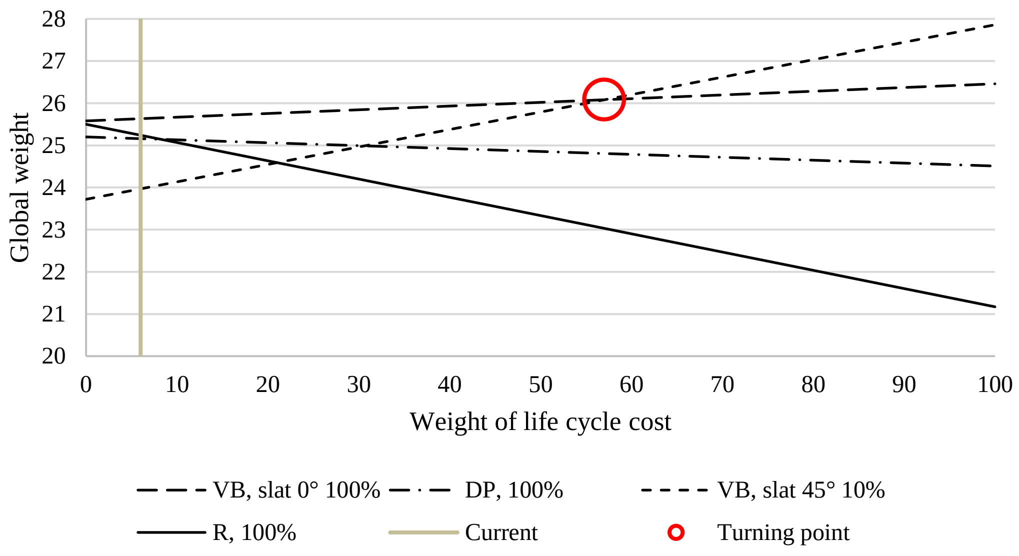

Figure 10. Sensitivity analysis with respect to life cycle cost

Table 8. Sensitivity of selected blinds' global weight regarding change in Life cycle cost weight

Blinds	Min 0	Current	Max 100	Global weight function
VB, slat 0°,100%	25.58	25.63	26.46	0.0088*weight of life cycle cost + 25.58
DP, 100%	25.20	25.15	24.51	-0.0069*weight of life cycle cost + 25.20
VB, slat 45°,10%	23.72	23.97	27.86	0.0414*weight of life cycle cost + 23.72
RC, 100%	25.50	25.24	21.17	-0.0433*weight of life cycle cost + 25.50

Conclusion

In this study, the performance of interior venetian blinds (VB) with slat of 0° and 45°, roller blind and double pleated blind was analysed with regard to visual comfort, thermal comfort, energy consumption and life cycle cost. The height of the blinds changed from 10% to 100% of the window's height. Later, the AHP method was utilized for ranking blinds and selecting the best solution based on the trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost. The results show that VB, slat 0°, drawn 100% (VB, slat 0°, 100%) performs better in reducing the glare probability and is the trade-off window blind among forty blind configurations. In performing the pairwise comparisons between visual comfort, thermal comfort, energy consumption and life cycle cost, visual comfort was specified as the most important one. Therefore, VB, slat 0°, 100% which had better performance considering visual comfort gained higher global weight. However, these results differ from presented results by previous studies. This occurs because this study not only compared various blind configurations, but also studied their impacts on visual comfort, thermal comfort, energy consumption and life cycle cost simultaneously. On the contrary, previous studies analysed mostly a single type of blind in correlation with an automatic control system integrated with electrical lighting or the HVAC system. For instance, the study conducted by Leslie, Raghavan, Howlett and Eaton (2005) shows that interior venetian blind with automatic control system can significantly decrease the total energy consumption in comparison with manually controlled blind. While the results of this study show that automatically controlled venetian, roller and double pleated blinds with different heights affected only the energy need for space heating and cooling marginally. Furthermore, the results of this study differ from presented those by Bessoudo et al. (2010). According to Bessoudo et al. (2010) a roller blind has better performance than venetian blind with respect to thermal comfort. While the results of this study show that, in an office room, changing window blind or its height has no significant effect on thermal comfort.

Furthermore, this study found AHP as a useful method in selecting the best blind based on the trade-off among visual comfort, thermal comfort, energy consumption and life cycle cost. Performing sensitivity analysis showed that VB slat 0°, 100% remains the preferred design alternative until the weight of energy and life cycle cost is below 0.37 and 0.57 respectively. However, change in thermal comfort weight has no impact in ranking of the blind configurations. Considering the visual comfort, the VB slat 0°, 100% is the trade-off blind as long as the visual comfort weight is above 4%. This occurs because by reducing the weight of visual comfort, blinds which have a smaller investment cost will gain higher weights. Hence, VB, slat 45°, 10% (drawn only 10% of widow height) becomes the trade- off blind when the visual comfort weight is below 4%.

Future work in this study will include the utilization of AHP with a multi-objective optimization algorithm for ranking and selecting a trade-off solution among a large number of solutions. Evaluating a large number of solutions increases the likelihood of finding suitable solution and facilitates the decision making process.

References

Alwaer, H. and D. Clements-Croome (2010). "Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings." *Building and Environment* 45(4): 799-807.http://dx.doi.org/10.1016/j.buildenv.2009.08.019

Arpacioglu, U. T. and H. Y. Ersoy (2013). "Daylight and Energy Oriented Architecture Design Support Model." *Gazi University Journal of Science* 26(2): 331-346

Avasoo, D. (2007). The European window energy labelling challenge. Proceedings of the European council for an energy efficient economy (ECEEE) summer study

Bessoudo, M., A. Tzempelikos, A. Athienitis and R. Zmeureanu (2010). "Indoor thermal environmental conditions near glazed facades with shading devices–Part I: Experiments and building thermal model." *Building and Environment* 45(11): 2506-2516.http://dx.doi.org/10.1016/j.buildenv.2010.05.013

Bhatt, R., J. Macwan, D. Bhatt and V. Patel (2010). "Analytic hierarchy process approach for criteria ranking of sustainable building assessment: a case study." *World Applied Sciences Journal* 8(7): 881-888

Bülow-Hübe, H. (2007). *Solar shading and daylight redirection*. Architecture and Built Environment, Lund University Lund, Sweden

Carlucci, S., F. Causone, F. De Rosa and L. Pagliano (2015a). "A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design." *Renewable and sustainable energy reviews* 47: 1016-1033.http://dx.doi.org/10.1016/j.rser.2015.03.062

Chan, Y.-C. and A. Tzempelikos (2013). "Efficient venetian blind control strategies considering daylight utilization and glare protection." *Solar Energy* 98: 241-254.dx.doi.org/10.1016/j.solener.2013.10.005

Chandel, S. and R. Aggarwal (2012). "Thermal comfort temperature standards for cold regions." *Innovative Energy Policies* 2: 1-5.doi:10.4303/iep/E110201

Chandratilake, S. and W. Dias (2013). "Sustainability rating systems for buildings: Comparisons and correlations." *Energy* 59: 22-28.http://dx.doi.org/10.1016/j.energy.2013.07.026

Chong, C. S. and Y. W. Shyang (2014). "Preliminary Model Framework: Natural Ventilation Performance Through Passive Design (Case Study: Tapak Semaian Mantin, Seremban)." *AJournal of Asian Scientific Research* 4(7): 339-347

Chung, T. and R. Ng (2016). "The application of analytic hierarchy process in daylighting performance assessment." *Indoor and Built Environment* 25(1): 50-68.DOI: 10.1177/1420326X14525061

Diva4Rhino (2016). [Computer software]. Retrieved from: http://diva4rhino.com/.

Dubois, M.-C. (2001). *Impact of shading devices on daylight quality in offices.Simulations with Radiance*. Department of Construction and Architecture, Lund University.Lund, Sweden

Elitfonster (2016). [Computer software]. Retrieved from: www.elitfonster.se.

Frontczak, M., R. V. Andersen and P. Wargocki (2012). "Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing." *Building and Environment* 50: 56-64.http://dx.doi.org/10.1016/j.buildenv.2011.10.012

García, J. A. O. (2010). "A review of general and local thermal comfort models for controlling indoor ambiences." *Air Quality. Ashok Kumar (Ed.)*.DOI: 10.5772/9763

GothenburgEnergy (2015). *Questions and answers about district heating system. [In Swedish: Frågor och svar om din fjärvärme]*. Retrieved from: https://www.goteborgenergi.se/Files/dok/Informationsmaterial/Broschyrer/Fr%C3%A5gor%20och%20svar%20fj%C3%A4rrv%C3%A4rme%20FINAL.pdf?TS=635189113969968750.

Grasshopper (2016). [Computer software]. Retrieved from: http://www.grasshopper3d.com/.

Heerwagen, J. H. (1998). Design, productivity and well-being: what are the links. *AIA Conference on Highly Effective Facilities, Cincinnati, Ohio, March*

Hoffmann, S. and E. S. Lee (2015). Potential energy savings with exterior shades in large office buildings and the impact of discomfort glare. Conference Proceedings BEST, Kansas City, Missouri

Hotman, E. (2005). Base reference analytical hierarchy process for engineering process selection. *International Conference on Knowledge-Based and Intelligent Information and Engineering Systems*, Melbourne, Australia, Springer.DOI: 10.1007/11552413_27

IDAICE (2016). [Computer software]. Retrieved from: http://www.equa.se/en/ida-ice.

Ishizaka, A. and P. Nemery (2013). *Multi-criteria decision analysis: methods and software*, John Wiley & Sons.DOI: 10.1002/9781118644898

ISO7730-Standard (2005). "7730. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria." *International Organization for Standardization: Geneva, Switzerland*

Jato-Espino, D., E. Castillo-Lopez, J. Rodriguez-Hernandez and J. C. Canteras-Jordana (2014). "A review of application of multi-criteria decision making methods in construction." *Automation in Construction* 45: 151-162.http://dx.doi.org/10.1016/j.autcon.2014.05.013

Kats, G., L. Alevantis, E. Mills and J. Perlman (2003). *The costs and financial benefits of green buildings: a report to California's sustainable building task force*. Retrieved from: http://evanmills.lbl.gov/pubs/pdf/green_buildings.pdf.

Kim, J.-H., Y.-J. Park, M.-S. Yeo and K.-W. Kim (2009). "An experimental study on the environmental performance of the automated blind in summer." *Building and Environment* 44(7): 1517-1527.http://dx.doi.org/10.1016/j.buildenv.2008.08.006

Lai, J. H. and F. W. Yik (2009). "Perception of importance and performance of the indoor environmental quality of high-rise residential buildings." *Building and Environment* 44(2): 352-360.http://dx.doi.org/10.1016/j.buildenv.2008.03.013

Lawrence Berkeley National Laboratory, L. (2016). [Computer software]. Retrieved from: https://windows.lbl.gov/software/comfen/comfen.html.

Lawrence Berkeley National Laboratory, L. (2016). [Computer software]. Retrieved from: http://www.energyplus.gov.

Leonelli, R. (2012). "Enhancing a decision support tool with sensitivity analysis." *University of Manchester*

Leslie, R., R. Raghavan, O. Howlett and C. Eaton (2005). "The potential of simplified concepts for daylight harvesting." *Lighting Research and Technology* 37(1): 21-38

Linden, W., M. Loomans and J. Hensen (2008). Adaptive thermal comfort explained by PMV. Proceedings of the 11th International Conference on Indoor Air Quality and Climate, Copenhagen

Mahdavinejad, M. and S. Mohammadi (2016). "Synthesis And Optimization Of Louver-Driving Mechanism For Innovative Daylighting System In Deepplan Building." http://hdl.handle.net/11413/1506

MakeitRational (2016). [Computer software]. Retrieved from: http://makeitrational.com/.

Mangkuto, R. A., M. Rohmah and A. D. Asri (2016). "Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics." *Applied Energy* 164: 211-219

Markelj, J., M. Kitek Kuzman, P. Grošelj and M. Zbašnik-Senegačnik (2014). "A Simplified Method for Evaluating Building Sustainability in the Early Design Phase for Architects." *Sustainability* 6(12): 8775-8795.DOI: 10.3390/su6128775

Monghasemi, S., M. R. Nikoo, M. A. K. Fasaee and J. Adamowski (2015). "A novel multi criteria decision making model for optimizing time–cost–quality trade-off problems in construction projects." *Expert systems with applications* 42(6): 3089-3104

Månsson, L. and Å. Schönbeck (2003). *Ljus & rum: planeringsguide för belysning inomhus*, Ljuskultur

Nikoofard, S., V. I. Ugursal and I. Beausoleil-Morrison (2014). "Technoeconomic assessment of the impact of window shading retrofits on the heating and cooling energy consumption and GHG emissions of the Canadian housing stock." *Energy and Buildings* 69: 354-366

O'Brien, W., K. Kapsis and A. K. Athienitis (2013). "Manually-operated window shade patterns in office buildings: a critical review." *Building and Environment* 60: 319-338

Ordouei, M. H., A. Elkamel, M. B. Dusseault and I. Alhajri (2015). "New sustainability indices for product design employing environmental impact and risk reduction: case study on gasoline blends." *Journal of Cleaner Production* 108, Part A: 312-320.http://dx.doi.org/10.1016/j.jclepro.2015.06.126

Podgórski, D. (2015). "Measuring operational performance of OSH management system–A demonstration of AHP-based selection of leading key performance indicators." *Safety science* 73: 146-166.http://dx.doi.org/10.1016/j.ssci.2014.11.018

Rahmani Asl, M., A. Stoupine, S. Zarrinmehr and W. Yan (2015). Optimo: A BIM-based Multi-Objective Optimization Tool Utilizing Visual Programming for High Performance Building Design. Proceedings of the 33rd eCAADe Conference, Vienna University of Technology, Vienna, Austria

Rhino3d (2016). [Computer software]. Retrieved from: https://www.rhino3d.com/.

Saaty, T. L. (2008). "Decision making with the analytic hierarchy process." *International journal of services sciences* 1(1): 83-98

Sabharwall, P., E. S. Kim, M. McKellar, N. Anderson and M. Patterson (2011). *Process heat exchanger options for the advanced high temperature reactor*. Retrieved.

Swedish energy agancy (2015). *Energy Situation [Title in Swedish: Energiläget]*. Retrieved from: https://www.energimyndigheten.se/contentassets/50a0c7046ce54aa88e0151796950ba0a/energilaget-2015_webb.pdf.

Swedish Environmental Protection Agency (2015). *The environment control [Title is Swedish: Styr med sikte på miljömålen]*. Retrieved from: http://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6666-6.pdf?pid=16477.

Veitch, J. A. (2001). "Psychological processes influencing lighting quality." *Journal of the Illuminating Engineering Society* 30(1): 124-140

Wong, J. K. and H. Li (2008). "Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems." *Building and Environment* 43(1): 108-125.http://dx.doi.org/10.1016/j.buildenv.2006.11.019

Yun, G., K. C. Yoon and K. S. Kim (2014). "The influence of shading control strategies on the visual comfort and energy demand of office buildings." *Energy and Buildings* 84: 70-85