OPTIMISING THE SCHEDULED OPERATION OF WINDOW BLINDS TO ENHANCE OCCUPANT COMFORT

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ABSTRACT

Artificial lighting can increase a building's total energy consumption. On the other hand, the availability of daylight in occupied spaces can reduce energy consumption while positively contributing to occupant wellbeing. However, daylight entering the space through windows needs to be reconciled with heat loss during winter and heat gain during summer, which may affect thermal comfort. In this research, a genetic algorithm is used to optimize the operation schedules of window blinds in a school classroom to enhance occupant visual comfort level. The objective of the optimization study was to reduce the energy consumption while maintaining the daylighting illuminance within the range of 100 lux to 2000 lux. EnergyPlus simulation software was employed as the daylighting and thermal performance calculation engine. The findings evidenced that the proposed genetic algorithm based schedule optimization reduced the HVAC and lighting energy consumption while giving preference to occupants' visual comfort. The results showed that the performance of the discussed method could also depend on different seasons. The genetic algorithm reduced the negative impact of solar gains on energy consumption in summer by closing the window blinds according to the solar angle.

INTRODUCTION

Buildings are responsible for 40% of the total global energy use (Oldewurtel et al., 2010) and account for 30% of the total emission of CO_2, which is one of the significant greenhouse gases responsible for anthropogenic climate change. Governments in major economies have taken initiatives to mitigate the impacts of climate change. Building regulations have been developed and/or updated to improve the thermal performance of buildings, with a view to reduce heating and cooling energy demand. With the sustained reduction in heating/cooling energy demand, the share of artificial lighting energy usage increases. In the USA for commercial building, artificial lighting accounts for 25-40% of the total electricity energy consumption (Ihm et al., 2009).

Previous research suggests that operation of movable insulations including venetian blinds, roller shades and curtain, have an impact on artificial lighting use and occupants' comfort (thermal and visual) with a resulting impact on energy consumption. Lee et al., (2013) studied the impact of blind operation on cooling load in buildings. It was found that blinds could significantly reduce the cooling load by decreasing the surface convection heat fluxes. Tzempelikos and Athienitis (2007) found that a reduction of 31% in total secondary energy can be achieved by applying active (closing the shades when beam solar radiation on window exceeds 120 W/m^2) lighting and shading control. Dubois (2001) also reported a reduction of between 23% and 89% in cooling energy by using shades. Cho et al., (1995) studied the effect of slat angle and absorptance on the buildings' cooling and heating loads. The results showed a reduction of 5% and 30% in heating and cooling loads respectively. From these figures, it is evident that a rational use of shading devices can result in significant energy saving. On the other hand, glazed surfaces without shading devices can decrease heating demand by employing passive solar design and making use of the renewable energy source, the Sun. This design strategy can lead to overheating in occupied spaces and a shading device can be used to reduce solar gains through windows.

Using shading devices will also increase the use of artificial lighting, which can affect a building's total energy demand. Having said that, one cannot deny the fact that people prefer daylighting to artificial lighting. A survey conducted by Cuttle (1983) to investigate the perceived attribute of windows found that 86% of the participants preferred daylighting over artificial lighting. Results from interviews conducted by Wells (1965) showed that 69% of the participants believe that it is better to work under natural lighting than electric lighting. In another survey conducted by Heerwagen and Heerwagen (1986) found that half of the subjects believed that natural lighting is better for psychological comfort, general health and visual health. The importance of daylighting for occupants' comfort is well acknowledged nowadays. For instance, Zhang and Birru (2012) assessed the performance of their open-loop analytical solar angle model and window geometry based control method on a real venetian blind test bed. Koo et al., (2010) presented a method for the automated control of venetian blinds focused on meeting the occupants' preferences rather than merely correcting the potential negative impact of daylighting. As these authors noticed during their study, the effectiveness of such automated daylight control is highly dependent on window orientation and season. A comprehensive control method should take into account the concomitant effect on artificial lighting and cooling system energy consumption.

Kim and Park (2009) classified research conducted on the blind operation into three categories- static and not optimal; dynamic and not optimal; and dynamic and optimal control. The studies classified under first category examined the impact of blinds on the building's cooling and heating loads (Cho et al., (1995), Newsham (1994), Lee et al., (2013)). The second category of research work considered blinds in a dynamic manner rather than static manner, and employed system identification by using artificial neural networks and/or fuzzy logic (Lee et al., (1998), Bauer et al., (1996), Guillemin and Morel (2001), Kurian et al., (2008). These studies did not minimise a cost function and cannot be considered as optimal control (Kim and Park (2009)). Kim and Park (2009) optimally control the slat angle of a blind system by minimising the heating, cooling and lighting energy. This study did employed an optimal control but has limitations in terms of considering occupants' visual or thermal comfort. The thermal comfort should have met as the authors used a purchased air system meaning it will meet the thermal comfort standards at any cost. However, the optimal slat position found may or may not meet the daylighting requirements i.e. whether the daylight situation at a sensor point or in a space is adequate or not.

Most of the research studies related to blind operation are focussed on slat control rather than controlling a blind as a whole (lowered/retracted), e.g. the research conducted by Cho et al., (1995), Kim and Park (2009). Controlling slats can only be useful during cooling season as they give the opportunity to block direct sunlight from entering the room (while blind fully down) and only allowing diffuse radiation to enter the occupied space (Lee and Selkowitz (1994)). This shows that controlling slat angle only can be useful to reduce cooling load. However, this method can also reduce the amount of useful daylight coming into the space, which in turn can increase the cooling load. Therefore, scheduling blind position throughout occupied hours can minimise heating, cooling and lighting energy.

This paper proposes a method to optimize the schedule of blind operation by using a genetic algorithm. The proposed method is used to reduce the energy consumption of a classroom while making sure that the visual comfort requirements of the occupants are met. The term scheduling of the blind operation means selecting the right combination of opening/closing of blinds at different facades that can be employed at each time interval of the scheduling duration. An optimal blind schedule can be the one that optimize particular objectives e.g. reducing the energy demand of the building while meeting the constraints (lux level at a reference point should be between 100lux and 2000 lux).

ENERGY MODEL DESCRIPTION

EnergyPlus (Crawley et al., 2001) is used as the simulation engine for the work presented in this research paper. EnergyPlus is an open source simulation software developed by Lawrence Berkeley National Laboratory. It was used to model the geometry of the building and to use as an evaluation engine for optimization process. It was chosen over a dedicated lighting simulation software tool (e.g. Radiance), due to its multi-domain (thermal, lighting) modelling capabilities.

Geometry and construction

The model considered in this research is a typical classroom of a school building. The school building is located in Cardiff, UK and is a BREEAM excellent rated building. The energy model of the whole school building is shown in *Figure 1*. The classroom has a width of 9.0m, a depth of 9.5m, and a height of 3.60m. It is assumed that the classroom has 30% WWR (Window-to-Wall ratio) on its southern and eastern facades and the windows consists of a double-glazing (3mm Generic PYR B Clear + 13 mm air gap + 3 mm Generic Clear). The physical properties of the inside slat-type blinds are summarised in Table 1. The blind has a thermal conductivity of 0.9 W/mK and a slat beam solar reflectance of 0.8 for both front and back sides.

Design assumption

The aim of the paper is not to study the characteristics of an HVAC system, therefore the cooling and heating demand of the zone was met by using a purchased air system (ideal load air system) in EnergyPlus. Ideal load air system meets the cooling and heating demand of a zone by providing the required supply air capacity at the specified temperature. The cooling and heating set points are defined according to the CIBSE guide A (CIBSE, 2006) i.e. 24°C for cooling and 22°C for heating. The mechanical ventilation was set at 1 air changes per hour (ACH). The classroom operation time is from 9:00 am to 5:00 pm and 9 people were considered in the room with an activity level of 60 W/m^2.

Lighting control strategy

The use of artificial lighting can affect the total energy demand both directly (increase in the energy consumption) or indirectly (increase of decrease in cooling and/or heating load) (Rapone and Saro, 2012). A continuous dimming control was employed to control the artificial lighting based on the lux level calculated at a reference point, the minimum power consumption from the lighting was 0.1129kWh. The reference point has an illuminance set-point value of 300 lux (CIBSE, 2006).

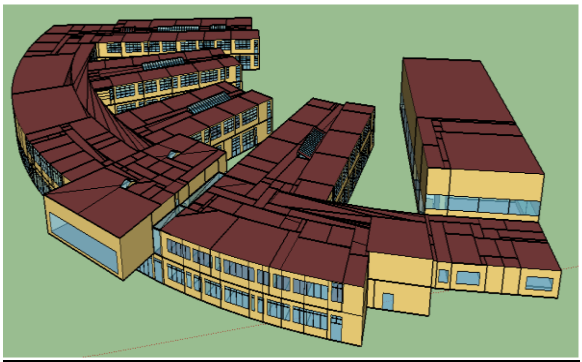

Figure 1: Energy model of the School building

Table 1:
Blind properties

Field	Unit	
Blind position	-	Inside
Blind orientation	-	Horizontal
Slat thickness	m	0.001
Slat width	m	0.025
Slat angle	deg	4
Slat conductivity	W/mK	0.9
Slat separation	m	0.01875
Blind to glass distance	m	0.015

OPTIMIZATION

Simulation-optimization is the process of finding the best set of parameters of a system, where the performance of the system is evaluated based on the output from a simulation model, without enumerating all possible solutions (Syberfeldt et al., 2009). Simulation-optimization consists in solving a complex real-world optimization problem by building a decision making methodology where (at least) one optimizer is interacting with (at least) one simulation engine. During the last 15 years, many case studies of simulation-optimization in various application fields have been carried out, including the optimization of dynamic control/operation problems (Azadivar, 1999, Kokko et al., 2000, Madsen et al., 2011). Tabu search, simulated annealing and evolutionary algorithms are some of the most common metaheuristics used for global optimization of simulations. The use of metaheuristics as optimizers for solving the simulation-optimization problem presented in this paper is justified by the highly combinatorial nature of the search space. The work described in this paper aims at integrating metaheuristics (the canonical generational Genetic Algorithm) with the EnergyPlus simulation software in order to solve the specific dynamic control problem- automation schedule of window blinds.

The constrained single objective optimization problem was implemented by using the open source objective-oriented Java-based framework jMetal (Durillo and Nebro, 2011). A java program was created to couple EnergyPlus and jMetal's generational genetic algorithm. A genetic algorithm (GA) is an iterative population-based optimizer, i.e. the search space of the problem is explored by maintaining and by iteratively updating a set of solutions (the size of this set, or population size, is one of the parameters of the genetic algorithm). New portions of the search space (i.e. new possibilities for automation schedules) are explored by combining/modifying existing solutions and by evaluating their performance.

Decision variables

The 18 decision variables used for this research are the blind position of each window for each occupied hour (i.e. one 9-hour schedule for each window). Blind positions can take 11 decimal values between 0 and 1 with a 0.1 step. They are discretized in the genetic algorithm as 11 integer values from 0 to 10. Consequently, a solution **x** of the optimisation is a vector of 18 real numbers.

Objective function

The objective function of the considered optimization problem is the run period primary energy consumption of the classroom. The run period primary energy consumption is the sum of heating, cooling and lighting energy consumption. This objective function is given by:
minimise:

$$f(\mathbf{x}) = Q_H(\mathbf{x}) + Q_C(\mathbf{x}) + Q_L(\mathbf{x}) \qquad (1)$$

where Q_H, Q_C and Q_L are the classroom's run period heating, cooling and lighting energy respectively.

The optimization can be subject to several constraints. Reinhart et al., (2006) provided a detailed overview of daylight performance metrics. Shikder et al., (2010) used daylight factor in their study to optimize a daylight-window for a patient window. Daylight factor is most commonly used daylight performance metric but it is calculated under worst sky conditions (overcast sky) and therefore other sky conditions (e.g. clear sky) may lead to different levels of daylighting in the occupied space, meaning it is not dynamic in nature. Reinhart et al., (2006) listed other dynamic daylight performance metrics. This research utilizes a dynamic daylight performance metric in order to maintain better visual comfort and was used as a constraint of the optimization problem.

The constraint considered in this paper is known as “Useful Daylight Illuminances” proposed by Nabil and Mardaljevic (2005). This metric ensures that the daylighting levels are ‘useful’ for the building users. The word useful refers to the fact that the daylighting is neither too dark (lux level <100 lx) nor too bright (lux level > 2000 lx) (Reinhart et al., 2006). The constraint used is to make sure that the number of hours when the threshold fell-short (>100 lx) or exceeded the maximum value, is zero i.e.
subject to:

$$\mathbf{N}_{\mathbf{hours\ (100>UDI>2000}} = 0 \qquad (2)$$

The constraint was calculated by the Energy Management system (EMS) inside EnergyPlus by using available sensors and actuators.

Constraint handling

Genetic algorithms in nature are unconstrained heuristic techniques and their success lies on the fitness of individuals (Mourshed et al., 2011). Therefore, it is difficult to solve a constrained optimization problem with an unconstrained algorithm. In order to tackle this problem, several methods were proposed by different researchers. In this paper a simplified and widely used method, the penalty function method, was employed to deal with the constrained nature of the problem. The penalty function used in the presented experiments consists in multiplying the original energy consumption by the number of hours when the Uniform Illuminance Index was either less than 100 lux or more than 2000 lux.

Genetic operators

A simple uniform crossover operator was used whereas a specific mutation operator has been designed for this research. The uniform crossover aims at creating two new pairs of schedules by randomly selecting blind positions from either of two existing schedules in the current GA population (with equal probability). The mutation operator consists in picking a blind position in an existing solution, the selected value is then perturbed by being set either to the nearest greater value or the nearest lower value. In a circular way, if the mutated value is above the upper bound (resp. below the lower bound), it is set to the lower bound (resp. upper bound). The GA's main parameters have been arbitrarily fixed (population size at 20, crossover probability at 0.9 and mutation probability at 0.05).

RESULTS AND DISCUSSION

The blinds' position schedules were optimized by using a simple GA, while artificial lighting were automatically dimmed based on the illuminance level at a reference point to save lighting energy consumption. The genetic algorithm looks to maintain the illuminance level between 100lux and 2000lux. The GA minimises an objective function i.e. sum of heating, cooling and lighting energy consumption.

Figure 2 shows the evaluation of the best fitness value for different runs. It is evident that on highest Q_C and clear sky days the GA reached an optimum solution after approx. 20 generations, whereas for other two days the GA found an optimum solution quite early in the optimization run. The fitness curve for clear day may look a straight line but in reality it is not, because of less energy demand on that day compared to the other simulated days. The fitness curves does not show a smooth decrease as one would have expected. This means that the algorithm is stuck in local optima for some generations. The decreased rate could be addressed by using an improved variant of genetic algorithm.

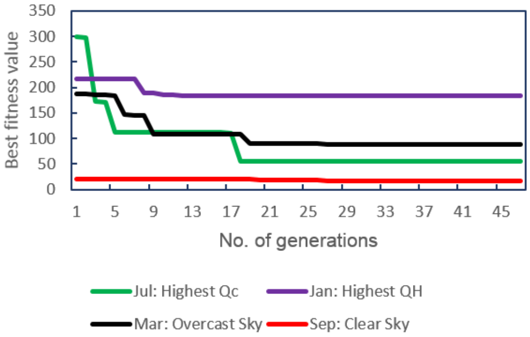

Figure 2: Best GA fitness values for different generations

Useful Daylight Illuminance (UDI) is considered as an effective performance indicator. Even though the difference between upper and lower threshold (100 lux and 2000 lux) is quite high, the genetic algorithm tried to keep the illuminance level below 1000 lux as shown in Figure 3- B. The suggested upper and lower range of UDI is based on the reported occupant preferences (Reinhart et al., 2006); however, studies show that an illuminance level of more than 1000 lux in uniformly lit rooms can lead to visual discomfort (Rea, 1982). The high value of illuminance can lead to glare discomfort due to reflections from the whiteboards in classrooms. Therefore, future works needs to include glare index in the problem formulation as a problem constraint.

In order to evaluate the relative performance of the GA, four different reference schedules were simulated: one with all blinds shut (lowered) throughout the day (WB), one without any blind (NB), south window blind shut (SBO) and west window blind shut (WBO). Figure 3-As show the obtained transmitted radiation rates, which is a sum of transmitted beam and diffuse radiation rates. The high transmittance from south façade window is during the early part of the afternoon whereas for west façade window the higher transmittance of solar energy is during the last part of the afternoon. In order to minimise the negative impact of excessive daylighting, the GA should close the blinds on south side window during the early part of the afternoon and later on for the west side window. This will also met the constraint (i.e. satisfying the visual comfort) by having no blind on one window at a time. The GA performed exactly the same as demonstrated in Figure 3- C(a).

The GA also adopted a same kind of blind opening and closing pattern on clear sky day and maintained same level of illuminance (Figure 3 A(b), B(b) and C(b)). On highest heating load day (Jan), the GA tried to close the south window blind, which was not expected as for as energy savings are concerned. The ideal case would have been to allow solar energy entering the space, which will reduce the heating load. However, the GA solution performed better in terms of constraint handling. The optimized solution has a lower number of hours when the UDI is either less than 100 lux or greater than 2000 lux as compared to other cases. The GA scheduling strategy consumed more energy but met the visual comfort requirements. The ideal (optimum) case for overcast sky day would have been without blinds, which has less energy consumption compared to the other cases. The GA closed blinds at different time of the day as shown in Figure 3-C(d). The GA is the second best in terms of energy consumption. The issue of determining whether the optimum schedule found by the GA is a correct one was addressed by introducing the predefined schedules (NB, WB, WBO and SBO) among the initial population of the GA. It was found that the final best solution obtained through GA with this setup was with no blinds throughout the day. The reason for the first results could be that the GA was stuck in the local minima and was unable to get out of it, but even then, it found the second best solution. GA has one unmet constraint and that was during the last hour of the day, SBO has two unmet constraints i.e. at the beginning of the day and at the end of the day (as one can predict). The discussed optimization method changes the blind position every hour depending on the outdoor environmental conditions and indoor illuminance level at a reference point. Changing blind position too frequently can distract building occupants and therefore the blind positon is changed every hour. Bakker et al., (2014) concluded that moving façade elements are a direct cause of distraction, however building occupants do get accustomed to moving façade elements.

The amount of time taken by simulation tools (EnergyPlus, RADIANCE etc.) to run 1000 evaluations to find an optimum solution is very high and a powerful computer may be needed to perform these runs e.g. an optimization run of the discussed optimization problem with 2000 generation took approximate 3 hours to complete on an 8-core 2.8GHz Intel Xeon computer. This limits the use of simulation tools for online or nearly real time control applications and therefore, efforts should be made to develop a (quicker) surrogate model to replace the simulation model.

The daylight illuminance uniformity over a horizontal reference plane of optimum GA solution for different days, expressed as the ratio of minimum to mean daylight illuminance, is shown in Figure 4. The GA solution shows a uniformly distributed daylight on the overcast day, this is because the variations in outside radiation are less as it consists of diffuse radiation only. In order to have a productive indoor environment for pupils, a uniformity of 0.3 to 0.4 is recommended for side-lit classrooms (Loe et al., 1999). None of the optimized solutions met this criterion as uniformity was not considered in the optimization problem. Future work should include daylight illuminance uniformity as an objective function along with energy consumption (for multi-objective optimisation problem) or constraint (for single objective optimisation problem). In this paper the slat angle is assumed to be constant i.e. 4 degrees for all simulation scenarios. In future, the proposed method will be combined with slat angle control. This would allow solar gains to enter into the living space in winter to reduce heating energy while reducing glare discomfort.

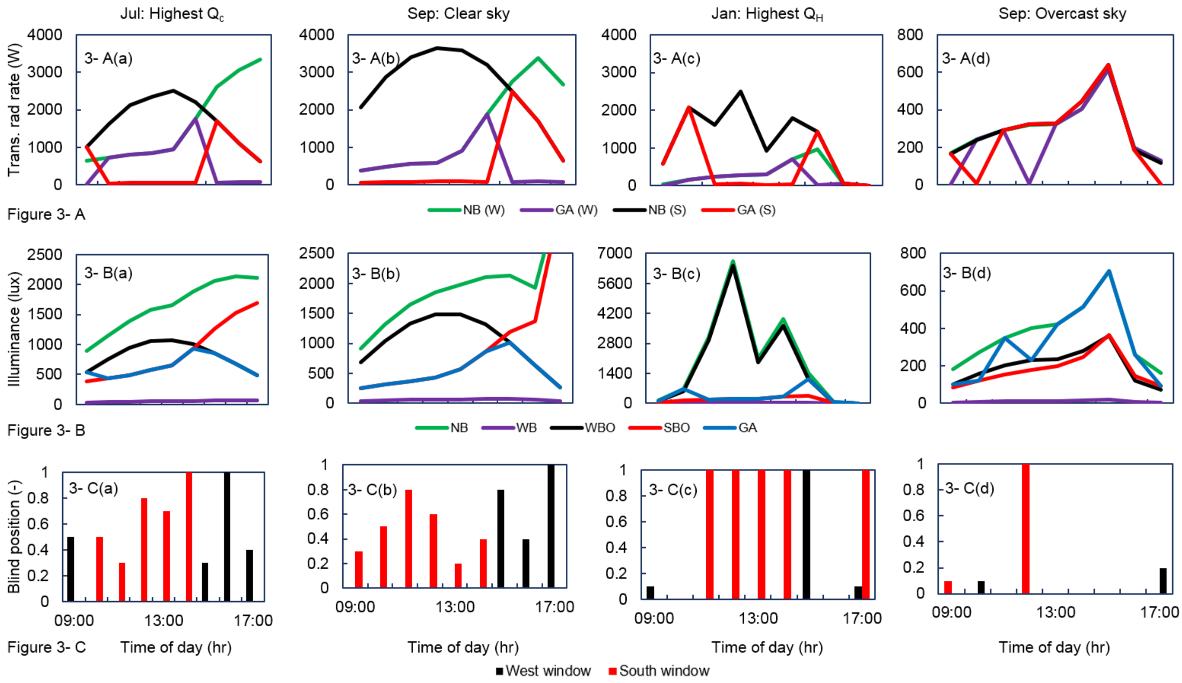

Figure 3: 3(A)- Hourly transmitted radiation rate, 3(B)- Hourly illuminance level at a reference point and 3(C) Hourly blind position schedules optimized by the GA.

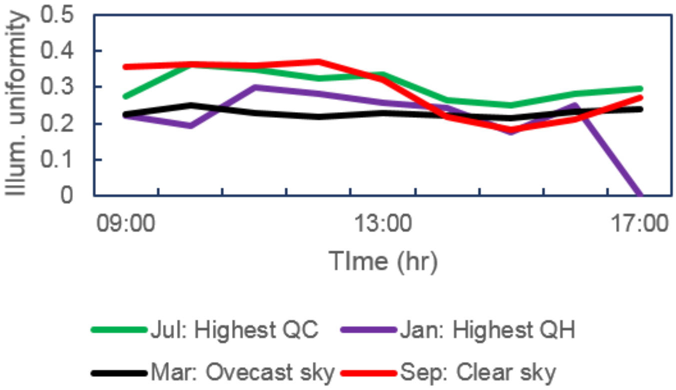

Figure 4: Daylight illuminance uniformity

Table 2:
HVAC and lighting energy consumption

		Energy consumption (kWh)			
		Highest cooling load day	**Highest heating load day**	**Overcast sky day**	**Clear sky day**
NB	HVAC Energy	61.27	45.97	33.02	22.17
	Lighting energy	1.01	3.33	1.86	1.02
WB	HVAC Energy	55.69	46.44	28.65	15.067
	Lighting energy	8.401	9.52	9.80	8.21
WBO	HVAC Energy	55.61	46.76	32.35	18.16
	Lighting energy	1.01	3.560	3.99	1.22
SBO	HVAC Energy	54.63	49.03	31.88	13.73
	Lighting energy	1.01	5.18	4.56	1.07
GA	HVAC Energy	52.82	48.40	32.36	13.03
	Lighting energy	1.01	4.23	3.08	1.27

CONCLUSION

This paper studies the schedule optimization of windows blinds operation by using genetic algorithm in order to reduce energy consumption from HVAC and lighting while maintaining the illuminance level within the comfortable range. Useful daylight index (UDI) was used as a constraint in the single objective optimization problem. EnergyPlus was used for daylighting and thermal simulation purposes. Four different sky and energy load days were studied and it was found that the proposed GA performed well on highest cooling load and clear sky days and scheduled the blind operation to reduce solar heat gains while maintain the desired illuminance level. The GA has more energy consumption on highest heating load day as compared to NB (no blind) case because it closed the blinds in order to provide better visual comfort by maintaining the illuminance level between 100 lux and 2000 lux. The study also highlighted the cause of underperformance of the GA on overcast day and addressed the issue by using predefined blind operation schedules in the initial population.

The paper also highlighted some of the future research directions. According to literature, lighting and shading control gets more acceptance when a degree of manual control is provided to the occupants to override automatic control (Galasiu and Veitch, 2006). The robustness of the schedules provided by the proposed GA based control against such uncertainties needs to be assessed.

The need of using a surrogate model to implement real time control was also stressed in the paper. The HVAC and lighting energy consumption for different cases are listed in Table 2. A saving of 13.55% of total energy consumption was achieved on the highest cooling day compared to NB case. Energy savings were more prominent on the clear sky day and 38.37% of energy consumption was saved. The importance of using other daylighting performance metrics was also pointed out in the paper.

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