Use of genetic algorithms for the optimum selection of the fenestration openings in buildings

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ABSTRACT

The objective of this work is to find the optimum window-to-wall area ratio that minimizes the energy cost for cooling, heating and daylighting. Both heating and cooling load are affected by the U-value and the solar heat gain coefficient (SHGC) of the glass whereas the amount of daylighting is affected by the coefficient of visual transmittance of the glass. For this purpose a genetic algorithm is used which is an optimum search technique based on the concepts of natural selection and survival of the fittest. In this work the genetic algorithm seeks to find a solution which minimizes the energy cost. The method is presented for three different types of fenestration with single glass, double glass and double glass for which the outer glass is reflective. A room with one external $10m^2$ double-brick wall is considered which is the usual case and size for an office room. This is the wall which carries the fenestration and the exercise was performed individually for the four cardinal directions using the weather conditions of Nicosia Cyprus. The results show that for all types of glasses considered the maximum optimum window-to-wall area ratio (WWR) is for the north direction, followed by the west direction whereas the smallest WWR should be in the east direction.

1. INTRODUCTION

A fundamental problem that has to be solved when designing a building is how much window area to use in each direction in order to maximize the use of daylighting but without compromising on the use of heating or air conditioning. Generally, fenestration affects the building cooling load, heating load and daylighting. By increasing the glass area with respect to the wall area, referred to as the window-to-wall area ratio (WWR) increases the cooling and heating loads, whereas the daylighting performance of the building improves thus requiring less electricity for lighting. Not many studies are reported in literature on this subject. A primary source of information is the ASHRAE Handbook of Fundamentals (2005) whereas another study which deals with windows size optimization is presented by Marks (1997). Daylight performance under different sky conditions is presented by Wittkopf (2007) whereas the impact of shading design and control is presented by Tzempelikos and Athienitis (2007). The window openings can be used also for passive cooling by cross-ventilation which affects the building cooling requirements (Nagai, 2006); this issue however is not considered in the present analysis as this is influenced by the occupants' behaviour. The effects of window size on the thermal load is well known while daylighting is relatively recently considered as a resource for energy conservation. Generally, daylighting is the illumination of the building interiors with sunlight and sky light and is known to affect visual performance, lighting quality, health, human performance and energy efficiency. In some countries there are codes regulating minimum window size, minimum daylight factor and window position to provide views to all occupants and to create a minimum interior brightness level. In terms of energy efficiency daylighting can provide substantial energy reductions, particularly in non-residential applications through the use of electric lighting controls. Daylight can displace the need for electric lighting at the perimeter zone with vertical windows and at core zone with skylights.

The objective of this work is to find the optimum WWR ratio that minimizes the energy cost for cooling, heating and daylighting. Both heating and cooling load are affected by the U-value and the solar heat gain coefficient (SHGC) of the glass whereas the amount of daylighting is affected by the coefficient of visual transmittance of the glass.

2. GENETIC ALGORITHMS

A Genetic Algorithm (GA) is inspired by the way living organisms adapt to the harsh realities of life in a hostile world. A genetic algorithm is an optimum search technique based on the concepts of natural selection and survival of the fittest. In this work the genetic algorithm used seeks to find a solution which minimizes the energy cost. Genetic Algorithms are stochastic optimization methods that mimic the process of natural biological evolution. Evolutionary algorithms operate on a population of potential solutions by applying the principle of survival of the fittest to produce better and better approximations to a solution. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from, just as in natural adaptation. GAs therefore, model natural processes, such as selection, recombination and mutation. Figure 1 shows the structure of a simple genetic algorithm. GAs work on populations of individuals instead of single solutions. In this way the search is performed in a parallel manner.

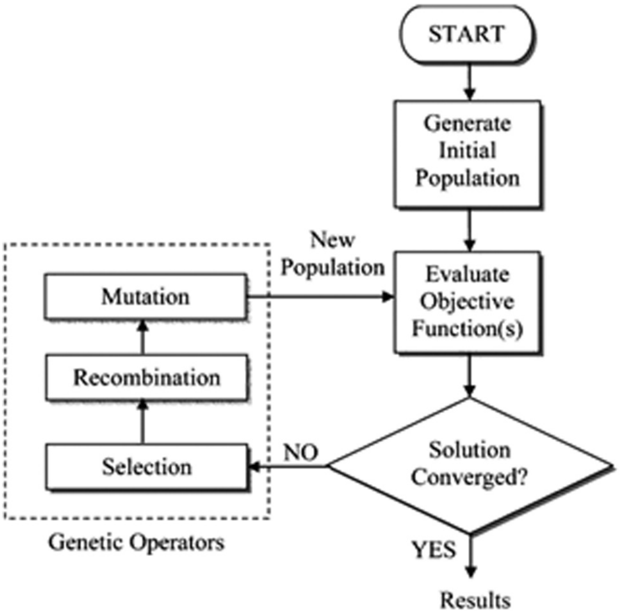

Figure 1 Problem solution using genetic algorithms

At the beginning of the computation a number of individuals (the initial population) are randomly initialised. The objective function is then evaluated for these individuals and the first/initial generation is thus produced. If the optimisation criteria are not met the creation of a new generation starts. Individuals are selected according to their fitness for the production of offspring. Parents are recombined to produce offspring.

All offspring will be mutated with a certain probability. The fitness of the offspring is then computed. The offspring are then inserted into the population replacing the old individuals, which in turns produce a new generation. This cycle is performed until the optimization criteria are reached. In the current work, the population consisted of 50 individuals. In the selection process, a generation gap of 0.90 was used, which means that 45 individuals in the old population would be replaced during each optimisation cycle. Finally, the mutation probability coefficient is equal to 0.01. More details on GAs can be found in Zalzala and Fleming (1997), and in Kalogirou (2005).

Genetic algorithms have been widely applied to optimization problems where methods that are more traditional fail. Genetic algorithm (GA) as an optimisation technique is widely used for optimisation of engineering problems. Many engineering design problems are very complex and therefore difficult to solve with conventional optimization techniques (Gen and Cheng, 1997). GAs have been used by the author for the optimal design of solar systems (Kalogirou, 2005). During the setting up of the GA the user has to specify the adjustable chromosomes, i.e. the parameters that would be modified during evolution to obtain the maximum value of the fitness function. Usually GAs are applied in cases where there are a number of chromosomes (adjustable parameters) which affect the solution of a problem and these are adjusted in order to find the best combination which optimises the problem. In this work however, only one chromosome is used, the WWR. Additionally the user has to specify the range of the WWR values called constraints. In the present work, this constraint is set equal to 0 to 60%.

3. METHOD

The method is presented for three different types of fenestration with single glass, double glass and double glass for which the outer glass is reflective. Detailed specifications of these assemblies are shown in Table 1. A room with one external 10m^2 double-brick wall is considered, which is the usual size for an office room, and the exercise was performed individually for the four cardinal directions using the weather conditions of Nicosia Cyprus. For this purpose the typical meteorological year (TMY) file for Nicosia was used and the horizontal global radiation contained in the TMY was analyzed in the four cardinal directions using the solar radiation processor of TRNSYS (Radiation mode 3, Reindl model). A representation of the wall/window construction together with the various modes of energy interactions are shown in Fig. 2. As it is indicated in Fig. 2 all other components of the building envelope, i.e., internal walls, floor and ceiling, are considered adiabatic, i.e., they do not contribute to the room load. Fenestration affects both the thermal load (cooling and heating) and daylighting and thus the energy cost (C). In equation form this is given by:

$$C = f\ (L, D) \quad (1)$$

where:

L: Thermal load (cooling and heating = Q_c+Q_h)

D: Daylighting.

The loads are estimated every hour. Equation (1) can be further analysed as:

A. Cooling load. This is given by:

$$Q_c = U_g.A_g.DT + U_w.A_w.DT + I.SHGC.A_g \quad (2)$$

where:

I: Solar radiation (W/m^2),
SHGC: Solar heat gain coefficient,
A: Area (m^2)
DT: Temperature difference between ambient temperature and required room temperature (°C).
In the present work the room temperature considered for cooling is 25°C. The subscripts g and w stand for glass and wall respectively. The first two factors of Eq. (2) are the transmission losses through the window and the wall whereas the last one is the direct solar gain entering the room through the window. In this work it is assumed that no internal curtains are used.

Table 1 Window properties considered

Number of glasses	Type of glass	Glass thickness (mm)	Type of gas	Gas thickness (mm)	U-value (W/m^2K)	SHGC	V_t
1	Clear	6	-	-	6.42	0.74	0.79
2	Both clear	6	Air	12	3.61	0.63	0.69
2	Inside clear Outside reflective	6	Air 5%, Argon 95%	12.7	3.08	0.46	0.42
Notes: 1. SHGC = solar heat gain coefficient, 2. V_t = visual transmittance							

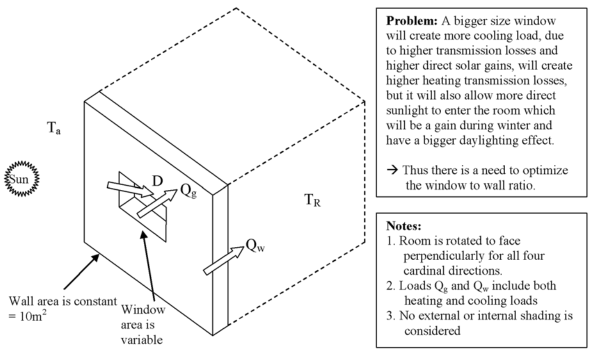

Figure. 2 Schematic representation of the wall-window construction

B. Heating load. This is given by:

$$Q_h = U_g.A_g.DT + U_w.A_w.DT - I.SHGC.A_g \quad (3)$$

All components are the same as in the previous case but the last component is not a loss in this case but a gain as it contributes to the reduction of the load. In the present work the room temperature (T_R) considered for heating 20°C.

C. Daylighting. The equation for daylighting, by considering a minimum rate of lighting R_v, is given by:

$$D = V_t . A_g . I - R_v \quad (4)$$

where:
V_t: Visual transmittance
R_v: Required light intensity in the room which can be taken for handbooks. In the present work a value of $10W/m^2$ is considered, which corresponds to 100 W for a $10m^2$ floor area room.
The hours of the day during which heating, cooling and daylighting loads are considered are from 8.00-17.00. The various factors used in this work are shown in Table 2.

Table 2 Room properties used in the optimization exercise

Parameter	Symbol	Value
Solar radiation	I	Taken from TMY
Solar heat gain coef.	SHGC	Taken from Table 1
Glass area	A_g	Variable
Glass U-value	U_g	Taken from Table 1
Wall area	A_w	Variable
Wall U-value	U_w	1.5 W/m^2-°C
Visual transmittance	V_t	Taken from Table 1
Required light intensity	R_v	100 W (=10 W/m^2*10m^2)

The energy sources considered are electricity for the cooling and daylighting and diesel for the heating. For the cooling a COP of the cooling system equal to 2.1 is considered whereas the efficiency of the boiler was equal to 85%. All loads are summed over the year and the totals are multiplied with the appropriate efficiency and cost of the energy source considered. The price of electricity considered is equal to 0.12 €/kWh whereas the price of diesel is 0.73 €/lt (0.0702 €/kWh), which are the current prices in Cyprus.
The objective here is to find the optimum A_g/A_w ratio (adjustable chromosome), mentioned before as WWR, which minimizes the energy cost C. For this purpose the energy loss or gain for the various modes of heat transfer are estimated every hour and from the total annual values the cost of energy is estimated as explained above. The whole model was set in a spreadsheet program in which the various parameters and equations are entered into different cells (see Fig. 3). As can be seen from Fig. 3, the adjustable chromosome (A_g/A_w ratio) is set in a different cell and the fitness function is the cell that contains an equation giving the total energy cost. During the execution of the program the genetic algorithm tries to find a value of the adjustable chromosome which minimizes the fitness function (total energy cost). For each new value of the chromosome, the spreadsheet is recalculated automatically. It should be noted that, the spreadsheet file described here needs to be constructed once. The only changes required for different problems would be to modify the cells with the window properties and the column of the solar radiation values.
In Fig. 3 the total energy cost in € is estimated from:

$$\text{Energy Cost} = [Q_{c(annual)}/2.1] .0.12 + [Q_{h(annual)}/0.85] . 0.0702 + D_{(annual)}. 0.12 \quad (5)$$

The constrain used is that WWR values vary between 0 and 60%. The run time of genetic algorithm and how quickly reaches the minimum solution depends on the initial conditions employed. Generally the run-time is about 2 minutes on a Pentium 3.2 GHz machine. The error recorded by using an initial WWR equal to 3.5% for a single glazing in the north direction is shown in Fig. 4.

As can be seen the GA focuses on the optimum solution very fast. The optimum solution is reached after 10 generations whereas a solution very near to the optimum is reached from the 7th generation. The value indicated on the graph is the cost of energy for heating cooling and daylighting for the room for one year.

Constants:	**Value**			
SHGC	0.74			
Ug	6.42			
Vt	0.79			
Cooling room temp.	25°C			
Heating room temp.	20°C			
RV	100 W			
Uw	1.5 $W/m^2{}^\circ C$			
WWR =	10.79 %	(adjustable chromosome)		
Total energy cost =	40.2531 €	(fitness function)		

Energy Estimation:

Time	Radiation	Ambient temp.	Cooling load	Heating load	Daylighting
1	0	7.5	0	0	0
2	0	7.0	0	0	0
…	…	…	..	……	…
8760	0	2.0	0	0	0
Totals (Wh):			386,849	98,325	85,798

Figure 3 Representation of the spreadsheet used for the optimization exercise

It should be noted that the GA was set to give the final solution after the minimum solution remained unchanged for 30 generations.

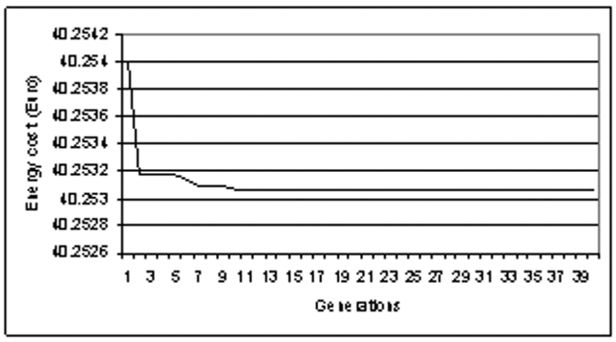

Figure 4 Plot of best fitness against the number of generations

The results for all types of glasses considered are shown in Table 2. These show that the maximum optimum window-to-wall area ratio (WWR) is for the north direction, followed by the west direction whereas the smallest WWR should be used in the east direction. As can be seen generally the better the glass the larger the area that can be used. As a general conclusion it can be said that glazing must be avoided or used with care in the south and east directions of a building.

Table 2 Results of the optimization

Single glass	
Direction	WWA (%)
S	3.80
E	2.84
W	8.59
N	10.79
Double glass (both glasses clear)	
Direction	WWA (%)
S	4.58
E	3.47
W	10.80
N	13.85
Double glass (inside glass clear, outside reflective)	
Direction	WWA (%)
S	6.42
E	4.93
W	15.09
N	19.86
Note: Wall area = 10 m^2	

4. CONCLUSIONS

In this paper a method to find the optimum window-to-wall area ratio that minimizes the energy cost for cooling, heating and daylighting is presented. A genetic algorithm is used for this purpose, which is an optimum search technique based on the concepts of natural selection and survival of the fittest. The method is presented for three different types of fenestration with single glass, double glass and double glass for which the outer glass is reflective. The exercise was performed individually for the four cardinal directions using the weather conditions of Nicosia, Cyprus. The results show that for all types of glasses considered the maximum optimum window-to-wall area ratio (WWR) is for the north direction, followed by the west direction whereas the smallest WWR should be used in the east direction. In fact the glazing in the south and east directions of a building affect to a large extent the thermal characteristics of buildings and must be used with care to avoid unnecessary thermal loads.

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