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SIMPLIFIED DESIGN OF A SPECULAR SLAT PROFILE CURVE USING 2D RAY TRACING AND GENETIC ALGORITHMS

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ABSTRACT

In this paper, we present a method of defining the profile curve of a static specular slat-type system. It uses an optimization procedure (GenOpt program was linked to JGAP (Java Genetic Algorithm Package) genetic algorithm) in order to modify the shape of a quadratic curve, which in turn is used to describe the slat profile. The aim is to achieve the following criteria:

1. To reduce summer two dimensional (2D) transmitted flux
2. To increase winter 2D transmitted flux
3. To increase the view through the system
4. To increase the upward part of 2D flux leaving the system (redirection ability).

INTRODUCTION

The building sector is responsible for 40% of the overall energy consumption (Eurostat, 2010 edition) and represents the biggest source of CO_2 emissions (European Commission's website on energy efficiency in buildings). Facing the challenge of reducing green house emissions, EU members agreed to implement the so-called "20-20-20" targets by 2020. These targets are, a 20% reduction in green house emissions based on 1990 levels, a 20% reduction in energy use due to energy efficiency and 20% of EU energy needs should be met by renewables. This "climate and energy package" was agreed by the European Parliament and Council in December 2008. It is evident that energy efficiency plays a crucial role in achieving real emission reductions at low cost (UNFCC, FCCC/KP/AWG/2007/43, 2007). Europe's 2020 Strategy , which was adopted in 2010, include the above mentioned targets while the recast of European Building Performance Directive (Directive 2010/31/EU ,2010) requires that member states ensure -among others- that by 2021 all new buildings will be 'nearly zero-energy buildings' starting with the public sector.

Office buildings have a high energy savings potential (Gratia E et al., 2003) with shading playing a crucial role. Shading can regulate solar gains by reducing cooling loads, provide daylighting and at the same time offer a visual connection to the external environment. However, the above phenomena are antagonistic and in many cases, during the design phase, the shading system selection is subject to a compromise between shading needs, daylight provision and comfort (Tsangrassoulis A.,2008). Lighting energy savings due to daylighting can be quite high (Doulos L et al., 2008), although too much daylight can cause glare problems. Therefore, any control of the distribution of light intensity can be beneficial. To facilitate these time-related complex demands, shading systems can be either automatically controlled (i.e. slat angle modification) or designed in such a way that, although static, they can offer a compromising solution.

Although the number of buildings that have dynamic facades is beginning to grow, the complexity of their design and the increased initial costs and maintenance needs prevent their widespread use, disregarding the user's reactions.

One of the most common systems adjusting solar gains together with daylight admission is the venetian blind system. Either exterior or interior, ordinary blinds have a curved section for mechanical stiffness and adjustment precision and a rather low efficiency in redirecting sunlight. This property is strongly depended upon the blind section and its material reflection properties. Nevertheless, visual connection with the exterior environment -crucial for human beings- can be restricted. To tackle this problem, perforation is used, restoring visual connection even when blinds are closed.

Due to the complexity of the continuous control, new designs for reflective blind sections have been proposed , such as these from Koester (Koester, H. 2004) or Kuhn (Kuhn T.E., 2006) offering unobstructed view , seasonal regulation of solar gains during the heating/cooling periods and daylight provision.

It is obvious that finding a blind section with the use of a predefined set of demands can be of great importance. A similar approach is used for the design of a luminaire's reflector. Since the design, testing and modification of a reflector shape is a tedious process (based on trial and error), an inverse method can be applied, at least, during the initial design phase. Using a light source with known intensity distribution, inverse design methods create the reflector surface shape by using a given photometric distribution as a prerequisite (Ashdown I (1994), Patowa G. et al. (2007), Wandachowicz K., (2003)). However, reflective blinds have a more complex behavior because the light sources (sun and sky) either change their position or their intensity distribution. In addition to this, arbitrarily shaped sections can considerably increase the number of intereflections making the calculation process time-consuming.

There are a number of algorithms available, capable of simulating the propagation of light flux through a model, using ray tracing techniques. These can handle a variety of surface optical properties, 3D geometries and light sources (Trace-Pro, Photopia, Photonmap, SPEOS) and provide light intensity distributions –among others- as output. In the case of luminaire reflector design, a kind of optimization/parameterization does exist, altering the intensity distribution produced by the initial design in a number of control points. This has an effect on the reflector's shape. Automation of this procedure can be performed by using an evolutionary algorithm and setting up an objective function directly related to the efficiency and/or the desired intensity distribution.

The approach that this paper proposes is based on the following assumptions and its target is to present a solution so as to simplify the initial design phase of slat's profile curve:

1. Only specular reflection is considered
2. Only direct solar radiation is taken into account
3. 2D ray tracing algorithm is used to estimate the angular distribution of the transmitted flux (Tsangrassoulis A. et al (2006), Wittkopf S. et al (2010) and view. These parameters define the objective function that the genetic algorithm tries to minimize, in an effort to satisfy certain criteria such as the reduction/increase of the transmitted 2D flux during summer/winter respectively, the increase of view and the increase of the upward part of 2D flux leaving the system (redirection ability).
4. A hybrid genetic algorithm was used, combining GenOpt (GenOpt, http://simulationresearch.lbl.gov/GO/new.html) together with JGAP (JGAP, http://jgap.sourceforge.net/).

The design approach as a whole is presented in figure 1.

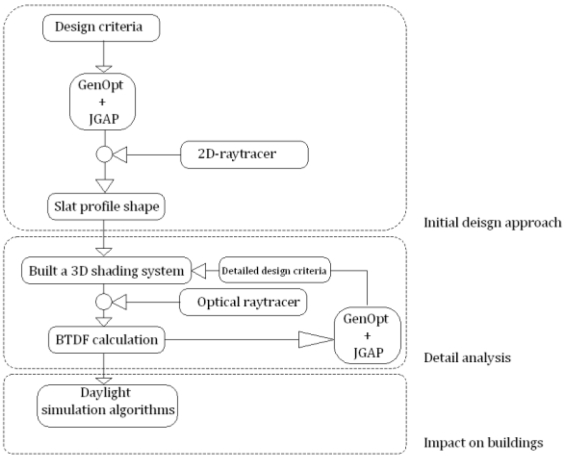

Figure 1. Schematic flow chart for the design of a slat type shading system

METHODOLOGY

The optimization problem was solved with a hybrid genetic algorithm. The backbone of the method presented is the GenOpt, since it can be coupled with a simulation engine via text files. The 2D raytracing program uses text files as inputs and prints delimited results into text files as well. The current version of GenOpt (3.1) doesn't include a genetic algorithm, therefore JGAP has been integrated into it. JGAP is a Genetic Algorithms and Genetic Programming component provided as a Java framework. GenOpt is divided into a kernel part and an optimization part. The kernel reads the input files that setup the problem, writes the simulation engine's input files, calls the simulation program, retrieves the results from the output files, logs the operations and prints results to the screen. The optimization part contains the optimization algorithms and exposes the kernel functionality to them. The code needed to couple JGAP functionality with GenOpt was implemented as a new optimization algorithm. This new algorithm retrieves the genetic algorithm (GA) configuration from GenOpt's input file and sets them to the JGAP. JGAP decides the values of the design variables for each population. The implementation code translates this population into GenOpt simulations and executes the calculation procedure. The retrieved results are sent back to JGAP which decides for the next population. The JGAP configuration is done in the same way like any other algorithm provided by GenOpt with an "algorithm" section in the command file.

The implemented genetic algorithm uses the typical GA operations. It starts with an initial population with random values for variables used to calculate the fitness (objective) function. After that, it applies the natural selector to the population used, to pick the solutions with the best fitness function. Then it applies the typical operators of crossover and mutation and adds random population if needed to get the desired population size. The JGAP's breeder, which applies the genetic operators, is further improved by cleaning double evaluations and getting a steady population size.

The above mentioned GA is further coupled in a hybrid operation with the GPSHookeJeeves which is a general pattern search algorithm and is provided by GenOpt. The GA operation is carried out in a multithreaded way but the provided pattern search uses only one thread. With some modifications to the original code, the GPSHookeJeeves algorithm operates as a synchronously parallel pattern search method which utilizes the multithreaded capability. This operation further improved the algorithm's performance for the current problem.

2D-ray tracing algorithm

The definition of the objective function, demands the calculation of 2D flux from the blind system which consists of two parallel horizontal slats of known profile curve. There aren't many 2d ray tracers available (Raytrace, http:// www.reimann.dk/gregers/projects/00Raytrace.lsp). Thus a simple 2D raytracer was developed for this reason and the calculation starts with the emission of a user defined number of parallel rays which are emitted from the entrance aperture.

For each ray emitted, an initial weight equal to 1 was assigned. The rays are traced through successive specular reflections and their weight is reduced according to the slat surface reflectance. The procedure is repeated until the ray weight becomes smaller than a preset value (i.e. ray absorbed) or exits the system. Consequently, the rays are recursively tracked through reflections and when they exit, their weight is accounted in a predefined bin of directions. All exit rays that have the same direction but different positions, are accounted in the same bin since the slat system is considered as a point source. Using only one bin (hemisphere), the 2D flux transmitted is calculated, while by increasing the number of bins, 2D angular flux distribution can be estimated.

The mathematical formulation of the used ray-tracing algorithm is quite simple. Slat section is described using a continuous function (in this case it is based on a quadratic equation):

$$y = f(x) \qquad (1)$$

When a ray intersects this equation at a point $(x_0, f(x_0))$, the slope of tangent and its normal are $f'(x_0)$ and $-1/\ f'(x_0)$ respectively. Since the reflection is considered as specular, the reflected ray ($\vec{R}$) is calculated using the incident ray ($\vec{I}$) and the normal ($\vec{N}$) according to the equation:

$$\vec{R} = \vec{I} - 2 \cdot \vec{N} \cdot (\vec{N} \cdot \vec{I}) \qquad (2)$$

The geometrical variables that affect the slat profile curve and are used for its shape optimization are presented in the following figure.

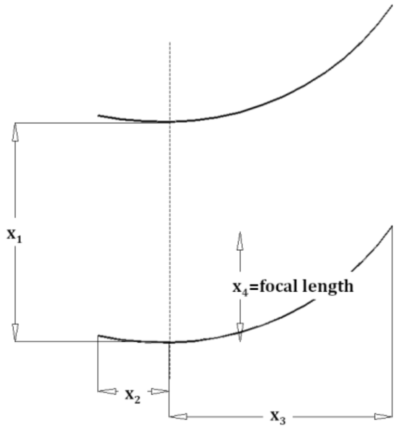

Figure 2. Geometrical parameters used for slat profile curve optimization.

The algorithm calculates the 2D flux transmitted through the system for two initial ray directions forming angles which represent the highest altitude of the sun during the summer and winter solstice on a vertical section normal to the window surface where the blind system will be placed. The weight of the transmitted rays is summed up for each one of the six bins as presented in the figure 3.

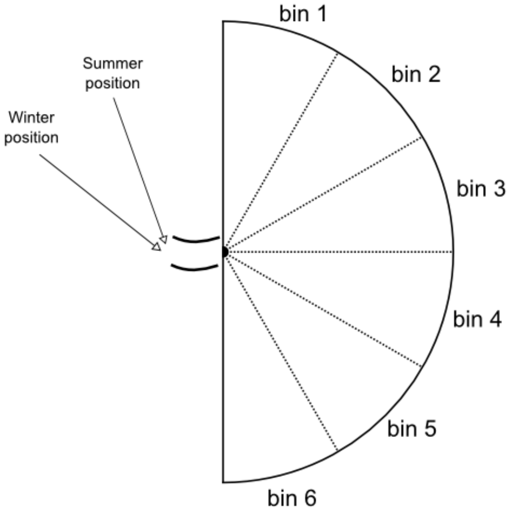

Figure 3. Definition of angular distribution of the transmitted flux.

The selection of these angles is crucial for the slat profile in order to handle solar radiation with seasonal selectiveness since the system is static. Depending on the fitness function, the initial design concept can be altered. For example two sun elevations representing the extreme positions for the shading period can be used (for example in Athens, Greece, shading is needed from May to September). In this case, the objective function can be modified to include only view, redirection ability and a predefined flux transmittance during the summer.

Optimization procedure

The initial number of rays emitted and the two directions are user-defined while the GA modifies the four parameters presented in figure 2. All four together correspond to a potential solution which is called a chromosome or an individual. Each set of potential solutions is called a population. Each chromosome consists of genes, and each gene represents a particular element of the candidate solution. An allele is the value of a gene.

Initially many individual solutions (chromosomes) are randomly generated to form an initial population. After calculating each individual's fitness function, the population evolves. To compute the next population, operators are applied to the current population.

The simplest form of genetic algorithm involves three types of operators: selection, crossover and mutation. The selection operator selects chromosomes in the population for reproduction. The fitter the chromosome, the higher the likelihood that they will be selected to reproduce. The crossover operator randomly chooses a locus, which is the position of a gene in a chromosome, and exchanges the subsequences before and after that locus between two chromosomes to create two offsprings. The mutation operator randomly changes the value of a gene in a potential solution. The algorithm starts with an initial slat-section shape (continuous function) which in this case is a quadratic equation:

$$y=x^2/4a \qquad (3)$$

Depending on the place and the orientation of the window where the shading system is going to be placed, two sun elevation angles are defined, representing the highest and the lowest elevation during the summer and winter solstice respectively. The algorithm then modifies all parameters that affect the slat profile shape in an effort to reduce the summer two dimensional (2D) flux transmitted (2D_sum), to increase the winter 2D flux transmitted (2D_win), to increase the view out through the system (View_out) and to increase the upward part of 2D flux leaving the system (redirection ability). Thus the objective function that the algorithm has to minimize is defined as follows:

$$f(x) = 3 -(1-2D\_sum)*weight\_sum - 2D\_win*weight\_win -View\_out*weight\_view \qquad (4)$$

where:

$$2D\_sum = \frac{\sum_{bin=1}^{6}(weight\ of\ rays)_{bin}}{Initialemmittedrays} \qquad (5)$$

$$2D\_win = \frac{\sum_{bin=1}^{6}(weight\ of\ rays)_{bin}}{Initialemmittedrays} \qquad (6)$$

View_out is the fraction of unobstructed view through the blinds as presented in the following figure 4.

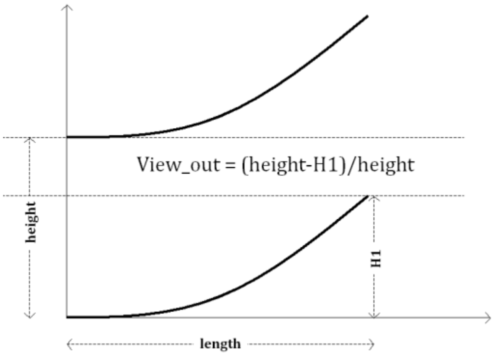

Figure 4. Definition of the parameter View_out

In this present case all weight variables (weight_sum, weight_win, weight_view) are considered equal to 1 while the number 3 was used to ensure that the objective function is always positive. To constrain unfeasible 2D flux distribution among the bins, it was decided that all designs with 2D fluxes transmitted into bins 3 and 4 that are larger than 2% of the incident flux, should be penalized together. This was realized by using penalty functions, one for each initial ray direction (i.e. sun elevation). Thus the new objective function is now defined as:

$$f(x) = 3 -(1-2D\_sum)*weight\_sum - 2D\_win*weight\_win -View\_out*weight\_view +p\_sum +p\_win \qquad (7)$$

where *p_sum* and *p_win* are the penalty functions for summer and winter respectively. These functions transform the constrain problem into an unconstrained one and penalise any solution with flux transmittance in bins 3&4 >0.02. Their definitions are as follows:

$$p\_sum = r*\left(\frac{\sum_{bin=3}^{4}(weight\ of\ rays)_{bin}}{Initialemmittedrays} - 0.02\right)^2 \quad if \quad \frac{\sum_{bin=3}^{4}(weight\ of\ rays)_{bin}}{Initialemmittedrays} >= 0.02$$

$$p\_sum = 0 \quad if \quad \frac{\sum_{bin=3}^{4}(weight\ of\ rays)_{bin}}{Initialemmittedrays} < 0.02 \qquad (8)$$

The same formulation applies for the winter penalty function as well. It must be pointed out that penalty functions have to be defined is such a way as to avoid adding discontinuities to the fitness function. Parameter r is the penalty coefficient.

Case study results

The method was used for a case with solar elevation angles (i.e. directions for initially emitted rays) equal to (75.4^0, 28.6^0) representing the highest and lowest position of the sun during the summer and winter solstice in Athens, Greece. The number of initial emitted rays can affect the simulation time and its estimation is based on a sensitivity analysis. The results are given in figure 5 presenting the variation of 2D_flux transmitted through the system for the two directions, against the number of initial rays. After a number of rays the convergence is obvious.

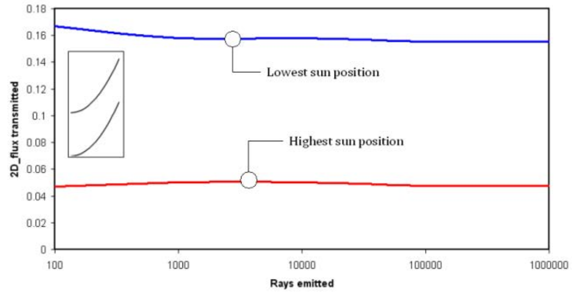

Figure 5. 2D-flux transmitted against initial emitted rays

The JGAP's algorithm searches globally for a near optimum solution and then GenOpt uses the result, to start a local search using a synchronous parallel version of GPSHookeJeeves algorithm. The used parameters are in the following table. At this point it has to be mentioned that all dimensions have been normalized to x_3 which is considered equal to 1.

Table 1
Parameters used in the case study

Geometrical parameters	**Optimization parameters**
Initial emitted rays = 100000	**GA parameters**
Limit ray weight=0.001	Max generations =100
$0.01<x_1<10$	PopulationSize = 40
$-1<=x_2<0$	BestChromosomesSelectorRate=0.50
$x_3=1$	CrossoverRate = 0.8
$0<x_4<10$	DesiredMutationRate = 0.20
Slat reflectance =0.98	Penalty coefficient r=10
	GPSHookeJeeves properties
	MeshSizeDivider = 2
	InitialMeshSizeExponent = 0
	MeshSizeExponentIncrement = 1
	NumberOfStepReduction = 1

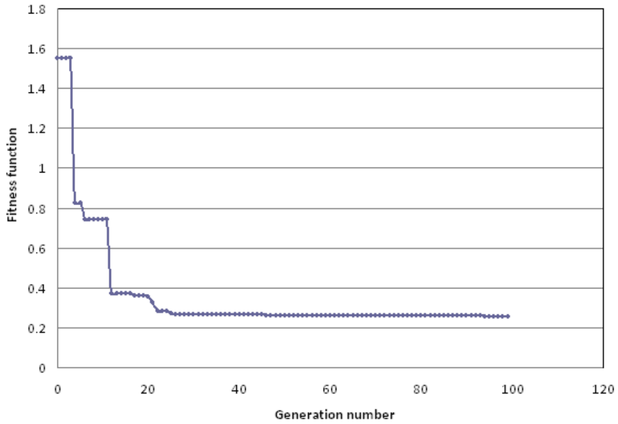

Figure 6. Minimization of the fitnesse function (GA best generation points).

The search space is relatively small, so the GA easily finds a good solution after 22 generations (880 simulations) as it is shown in Figure 6. However, 4000 simulation runs have been applied by the GA, in an effort to minimize the probability finding a suboptimal solution for the current problem. When the GA has ended, the pattern search is applied in an effort to refine the minimum value. Ray tracing started with 100000 rays for each one of the two initial directions and the penalty coefficient was equal to 10. Minimum value for the objective function was achieved with the following parameters $x_1=0.71$, $x_2=-0.0031$, $x_3=1$, $x_4=1.53$. View_out is 77% while the value for 2D_sum and 2D_win was 0.002 and 0.98 respectively. The solution is presented in the following figure.

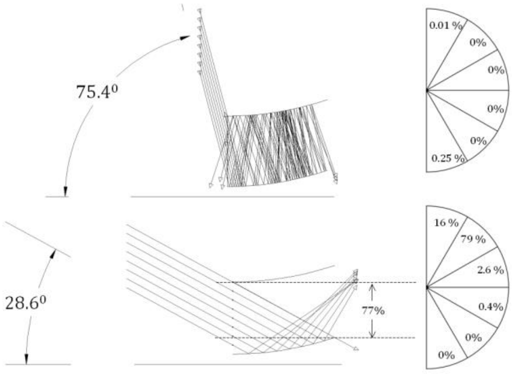

Figure 7. Reflective parabolic slat shape as defined by the objective function

CONCLUSIONS

Starting from a quadratic equation and a set of simple rules, the profile shape of reflective slats can be determined. These rules are based on the general approach of reducing solar gains during the summer together with the maximization of view out. A 2D ray-tracing algorithm, linked with a hybrid GA-pattern search method, can be used to minimize an objective function which takes into account the flux transmitted during the summer and winter, view out and the angular distribution of 2D flux leaving the system. By introducing penalty functions for some parts of the transmitted flux, the redirection ability of the system can be altered. This approach can effectively cover the design space offering a family of solutions that fulfils the set of the design criteria and can be the starting point for a more detailed analysis.

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