EVOLUTIONARY ADAPTIVE RADIATION PRINCIPLES USED FOR BUILDING FACADE OPTIMIZATION

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ABSTRACT

The growing amount of carbon emission from building sector due to insufficient high-performance design has been contributing to the CO_2 issue in the United States. One reason is lacking of energy performance optimization at the early design stage. In building optimization problem, there are numerous optimal design variables have to be achieved. It is necessary to reduce the optimization computation time so the workflow of the initial design process is not hampered. This paper introduces an analogy of "adaptive radiation" (AR), a principle known in evolution of ecological diversity, which describes the process how a single ancestor diverges into an array of species that are adapted to a variety of environments. The principle of AR is implemented in simulation-based optimization process with the goal of reducing the computation time. A case study of office building façade is presented. The efficiency, in terms of robustness and computation time of the AR algorithm, has been compared to the efficiency of the sole use of GA. Results demonstrated that AR can solve the optimization problems with significantly less computation time than GA.

INTRODUCTION

Building industry is the largest energy-consuming sector in United States and has a substantial impact on the environment. Residential and commercial buildings account for almost 40% of total U.S. energy demand and 40% of U.S. carbon dioxide (CO_2) emissions [DOE, 2011]. It is critical for building industry to improve energy efficiency and provide means for sustainable developments in the built environment.

It's a well-established belief that building façade plays a key role in building energy efficiency. In architectural practice, most of the design parameters of façade such as window-to-wall ratio, glazing material, thermal level and shading systems are accomplished in the early-design stage. The geometry of facade, dimensions of elements and the ratio between opaque and transparent area are crucial because they exploit the solar heat gain and provide daylight for the indoor environment. These parameters interact on each other, thus requiring optimization to achieve optimal or near optimal combinations in the early design stage while avoiding extensive modifications during building performance simulation process. Generally, the computation time will increase when the number of design parameters rises. There is a significant need to reduce the simulation computation time so the workflow of the initial design process is not hampered.

Genetic algorithm (GA) is widely applied for its efficiency and reliability in solving building optimization problems with discrete parameters [Caladas and Norford, 2002], [Rapone and Saro, 2011], [Attia, et al., 2012]. One crucial disadvantage is the large amount of computation time to be spent on the entire simulation process. Even though GAs have been verified one of the most efficiency optimization methods, they frequently require hundreds or thousands of simulation runs in order to achieve the optimal or near optimal result, which means weeks and months will be consumed. It is essential to find a more effective method to reduce the computation time, while not harming the complexity of the simulation model and the precise of the optimization result.

In this paper, a principle known as "adaptive radiation" is implemented, which describes the process how specific species are evolutionary adapted to ecological niches [Schluter D., 2000]. While GA treats parameters equally in the optimization process, AR group the parameters in a niche by their natural character. Similar to the evolutionary species, the form of the different façade orientations is one niche in the building envelope optimization problem. Parameters such as glazing type, insulation thickness and air infiltration keep the same for each façade orientation, while parameters such as window dimension and shading geometry are different for each orientation.

A typical office building façade with two different shading systems was implemented in this study. For both shading systems, three design strategies are evaluated: (1) window-to-wall ratio, (2) geometry of the shading system, and (3) type of glazing. Moreover, shading systems parameters are evaluated based on a complex shading system and a simple shading system respectively.

The outline of this paper is as follows: First, an overview of this optimization algorithm is provided. Then, the methodology of optimization algorithms and an evaluation criterion are explained. The calculation results for the case study and discussion of the results are then provided. The conclusions are finally summarized.

METHODS

Adaptive Radiation

Adaptive Radiation (AR) was originally developed to model the process of specific species are evolutionary adapted to ecological niches. While GA treats variables equally in the optimization process, AR groups the variables in different niches by their natural characteristics. AR then divides the entire optimization process into different generations by these niches. For these parameters, AR won't do optimization for all of them but rather do interpolation to achieve the optimization solutions based on the optimization results of a number of them. This process can largely reduce the computation time, since it can find the common features of optimization solutions and avoid repeating simulation runs for similar parameter settings.

An Adaptive Radiation procedure for building façade optimization is as follows:

• 1st Generation: Do optimization for all thermal parameters such as glazing materials or insulation levels. Those parameters will remain the same for all the walls, while not considering the impact of orientation. In this generation, the optimal solutions for glazing types, insulations and infiltration can be achieved.

• 2nd Generation: In this generation, select several windows on typical locations of the building facades. For example, select windows on the four orientations on top, middle and ground floors. Keep the glazing types and thermal materials achieved from the 1st Generation unchanged, and do optimization for design parameters such as window-to-wall ratio, depth and angle of shading elements. Due to the different annual solar heat gain for each window, different optimization solutions for selected windows can be achieved at this step.

• 3rd Generation: Based on the optimization result achieved from the 2nd Generation, make interpolation to get the optimal or near-optimal solutions for the rest of the windows located on the same floor. Since the daylight or shadow placed on the façade varies gradually, the annual solar heat gain also varies gradually on the façade, which may lead to a gradual change of the design parameters such as window-to-wall ratio, shading depth and angle of shading elements. For an entire building with complexity façade design, computation time can be largely reduced by this interpolation method.

• 4th Generation: Made interpolation and achieve the optimal or near-optimal solutions for windows between different floors. Repeat the process until optimal solutions for all windows are achieved.

The main advantage of AR is that computation time can be largely reduced by the method of interpolation, which avoids repeating similar simulation process happened before. Fig. 1 shows the workflow of the Adaptive Radiation.

In this workflow, the 3D/CAD modeling module (Rhinoceros + Grasshopper) first generates the input variables and the façade model. Simulation module (EnergyPlus and Radiance) then perform the evaluation of these parameters, and returns its fitness function value, which in the simplest case is the annual energy demand of heating, cooling and lighting. This value is sent to the AR, which uses it to guide the search progression. When the AR reaches the last population, the corresponding results can be fed back to the 3D/CAD modeling module to perform visualization models for the architects.

At present, there are limited user interfaces specifically designed for the evolutionary optimization in architectural design area. This workflow can present a visualization platform between 3D/CAD modeling, building simulation and optimization for the architects, and provide quick feedback of architectural design parameters, which help architects to make selections for their design and scrutinize the results clearly.

Setting for the adaptive radiation

An Adaptive Radiation is implemented in this study to test its ability and efficiency to find optimal or near-optimal solutions. There are 20 generations for each variation in the optimization procedure. A conventional single-objective genetic algorithm is compared to evaluate the performance of the adaptive radiation.

Elitism method, which always transfers the fittest member of a population to the next generation, is used in the optimization process. This feature ensures that the best solutions are transferred to the next generation. Furthermore, the optimization algorithms used in this study has these features:

• The positioning of the crossover of the two parent genes is set to occur randomly.

• A mutation process is used in the GA. The gene mutation probability after the crossover process is set for 1%, which is common for this size of problem.

• The GA stops the search process when the best solution in a series of three generations is not improved by more than 1%.

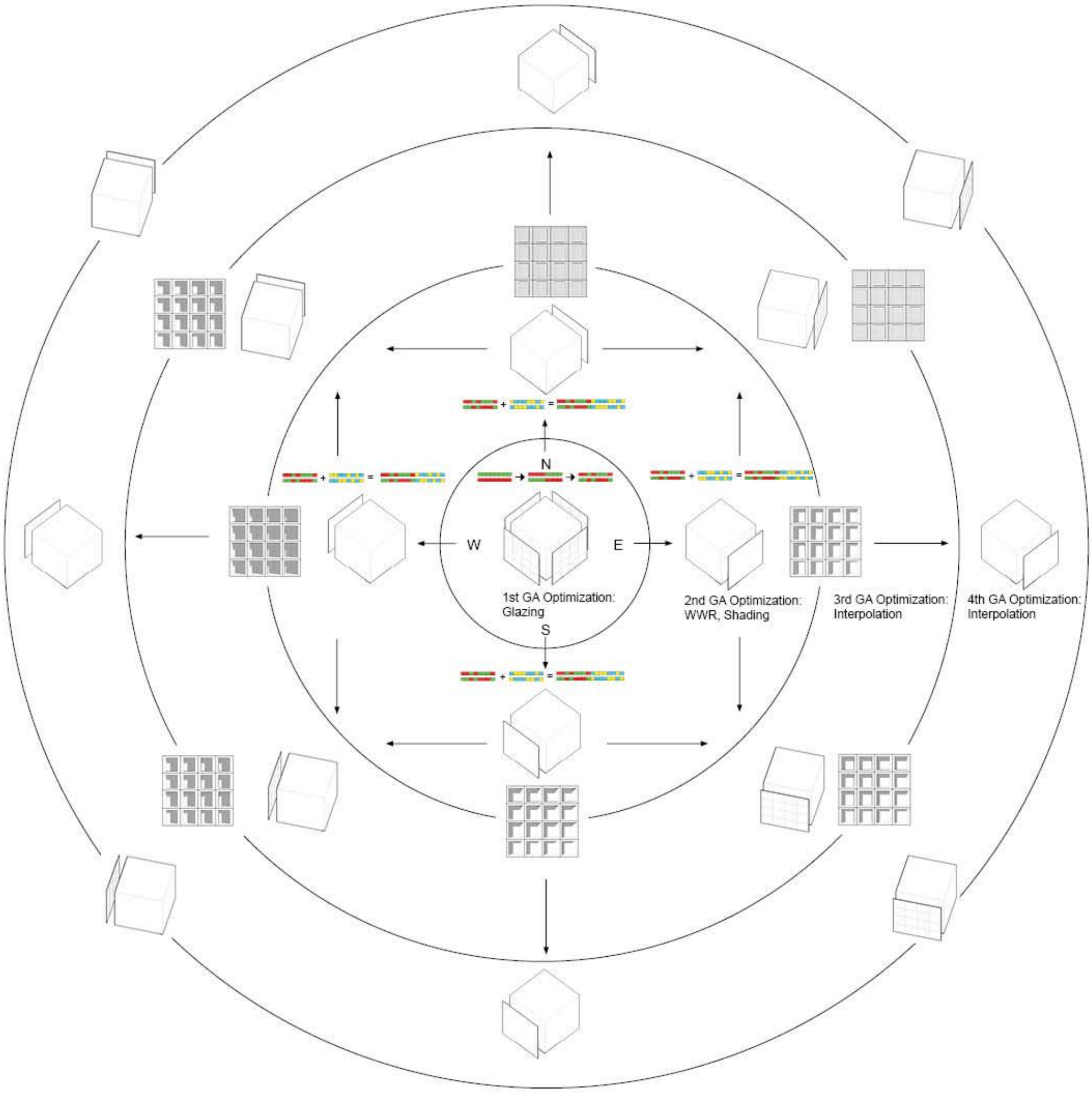

Figure 1 Workflow of the Adaptive Radiation

Test room definition

A single-occupant office room with an area of 10 m^2, a volume of 36 m^3 and a window area of 3.2 m^2 is selected as the test room. For the internal heat gains, the office room is assumed to have a computer (with monitor) with a heat gain of 240 W, an artificial light with a heat gain of 13 W/m^2, and a person with a sensible heat gain of 80 W. The room is assumed to be occupied on working days between 8 AM and 5 PM with a 1 hour break at noon.

Optimization problems

The proposed method is evaluated on two facade optimization cases, one with simple shading system and another with complex shading system. The simple shading system facade (Group A) has six parameter settings and 129,600 possible combinations totally. The complex shading system facade (Group B) has seven parameters and 655,200 possible combinations totally.

Parameters of Group A include the glazing types (parameter 1), insulation (parameter 2), infiltration (parameter 3), depth of overhang (parameter 4), depth of fin (parameter 5), and fin angles (parameter 6).

Parameters for Group B include the glazing types (parameter 1), insulation (parameter 2), infiltration (parameter 3), window-to-wall ratio (WWR) (parameter 4) and depth of shading (parameter 5). Also, to achieve a balance of thermal and daylight environment, each window will be slightly rotated along X-axis and Y-axis. Therefore there are two more parameters: rotated degree along X-axis (parameter 6), and rotated degree along Y-axis (parameter 7). **Table 1** shows the physical properties for the parameter settings

Table 1
Parameters and parameter settings

PARAMETER		PARAMETER SETTINGS												
Group A														
Glazing (parameter 1)		1	2	3	4	5	6							
U-value	[W/m^{2}K]	2.2	1.57	1.2	1.66	1.2	0.7							
SHGC	[-]	0.2	0.31	0.31	0.62	0.52	0.51							
Light transm.	[-]	0.25	0.62	0.62	0.68	0.58	0.58							
Insulation (parameter 2)		1	2	3	4	5	6							
U-value	[W/m^{2}K]	0.7	0.46	0.37	0.32	0.26	0.19							
Infiltration (parameter 3)		1	2	3	4									
ACH	[-]	0.25	0.18	0.15	0.12									
Fin (parameter 4)		1	2	3	4	5	6	7	8	9	10			
Depth	[mm]	100	200	300	400	500	600	700	800	900	1000			
Overhang (parameter 5)		1	2	3	4	5	6	7	8	9	10			
Depth	[mm]	100	200	300	400	500	600	700	800	900	1000			
Fin angle (parameter 6)		1	2	3	4	5	6	7	8	9				
Angle	[°]	30	45	60	75	90	105	120	135	150				
Group B														
Glazing (parameter 1)		1	2	3	4	5	6							
U-value	[W/m^{2}K]	2.2	1.57	1.2	1.66	1.2	0.7							
SHGC	[-]	0.2	0.31	0.31	0.62	0.52	0.51							
Light transm.	[-]	0.25	0.62	0.62	0.68	0.58	0.58							
Insulation (parameter 2)		1	2	3	4	5	6							
U-value	[W/m^{2}K]	0.7	0.46	0.37	0.32	0.26	0.19							
Infiltration (parameter 3)		1	2	3	4									
ACH	[-]	0.25	0.18	0.15	0.12									
WWR (parameter 4)		6	7	8	9	10								
WWR	[-]	60%	70%	80%	90%	100%								
Shading (parameter 5)		1	2	3	4	5	6	7	8	9	10			
Depth	[mm]	100	200	300	400	500	600	700	800	900	1000			
X-axis (parameter 6)		1	2	3	4	5	6	7						
Angle	[°]	0	10	20	30	40	50	60						
Y-axis (parameter 7)		1	2	3	4	5	6	7	8	9	10	11	12	13
Angle	[°]	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60

RESULTS

Results of enumerative search

In this study, the computation time and optimization result of genetic algorithm and adaptive radiation are compared. Two façade cases of an office room are optimized. One case is with simple shading system and another one with complex shading system. Two optimization runs are implemented for each case to verify the accuracy of the optimization result.

The results of two genetic algorithm runs show that, for the simple shading system (Group A) with six parameters, it needs 2280 or 1640 simulations to find the global optimum, respectively. The energy demand of optimal solution is 62.6 kWh/m^2 for the first run and 64.3 kWh/m^2 for the second run. For the complex shading system (Group B) with seven parameters, it needs 2220 or 3500 simulations to find the global optimum, respectively. The energy demand of optimal solution for the first run is 58.4 kWh/m^2 and 59.9 kWh/m^2 for the second run. The difference with the average energy demand for each run is 2.7% and 2.6% respectively.

Adaptive radiation result for the simple shading system (Group A) with six parameters shows that, it needs 720 or 740 simulations to find the global optimum for each run respectively. The energy demand of optimal solution for the first run is 58.5 kWh/m^2 and 59.9 kWh/m^2 for the second run. Adaptive radiation result for the complex shading system (Group B) with seven parameters shows that, it needs 820 or 780 simulations to find the global optimum respectively. In step 1 for Group A, the global optimum has the parameter settings for glazing, insulation and infiltration are P1:6, P2:6, P3:4. In step 2 for Group B, the global optimum has the parameter settings for glazing, insulation and infiltration are also P1:6, P2:6, P3:4. The energy demand of optimal solution is 58.8 kWh/m^2 for the first run and 59.0 kWh/m^2 for the second run. The difference with the average energy demand for each run is 2.3% and 0.5% respectively.

Performance of adaptive radiation

Table 2 and **Table 3** show the results of Group A. **Table 4** and **Table 5** show the results of Group B. **Table 2** and **Table 4** show the results of optimization runs accomplished with GA. **Table 3** and **Table 5** show the results of optimization runs accomplished with AR. The proposed parameter settings are shown to illustrate the high probability that the AR will find a solution close to the global optimum. For Group A, the optimal solutions of AR show a reduction of the energy demand of 6.5% and 6.9% for two optimization runs, when comparing with the optimal solutions of GA. For Group B however, the optimal solutions of AR show an increase of the energy demand of 0.7% for the first run, and a reduction of 1.5% for the second run. It shows that, comparing with GA, AR has more potential in achieving global optimum. Also, even though AR cannot always guarantee to find a solution closer to the global optimum than GA, the result of AR is still very closed to GA, which is smaller than 1%.

For Group A, 6 out of the 8 runs in GA show a clear tendency of parameter settings P1:3, P2:6, P3:4. Glazing no. 3 is recommended in all the optimization runs for the problem with three orientations. Glazing no. 6 is recommended only in the runs for west orientation. For AP, the runs of step 1 show a clear tendency to glazing no. 6, which is based on the rule that same glazing type should be used for all orientations.

For Group B, 7 out of the 8 runs in GA show a clear tendency of parameter settings P1:6, P2:6, P3:4. Glazing no. 6 is recommended in all the optimization runs for the problem with three parameters. Glazing no. 3 is recommended only in the second runs for west orientation. For AP, the runs of step 1 also show a clear tendency to glazing no.6, which is applied for all orientations.

For both Group A and Group B, the global minimum for the insulation and infiltration have the same tendency in both GA and AR optimizations, which recommends a lower heat transfer and infiltration rate for the entire building envelope.

Table 2
GA Results for the problem with six parameters (Group A).

Group A								Q_{Total}	# Gener.	# Sim.	Total simulation number
	Orientation	P1	P2	P3	P4	P5	P6	[kWh/m^2]	[-]	[-]	
Run 1	South	3	6	4	3	10	7	59.4	40	800	2880
	East	3	6	4	7	10	1	61.1	65	1300	
	North	3	6	4	3	10	7	71.2	19	380	
	West	6	6	4	10	10	9	58.7	20	400	
							Av.	62.6	Total	2880	
Run 2	South	3	6	4	3	10	7	59.4	10	200	1640
	East	3	6	4	10	6	1	66.6	39	780	
	North	3	6	4	3	10	7	71.2	20	400	
	West	6	6	4	10	4	1	60.1	13	260	
							Av.	64.3	Total	1640	

Table 3
AP Results for the problem with six parameters (Group A).

Group A								Q_{Total}	# Gener.	# Sim.	Total simulation number
Step 1	Orientation	P1	P2	P3	P4	P5	P6	[kWh/m^2]	[-]	[-]	
Run 1	All	6	6	4	6	7	9	64.4	10	200	
Run 2	All	6	6	4	9	9	9	73.2	11	220	
Step 2	Orientation	P1	P2	P3	P4	P5	P6	[kWh/m^2]	[-]	[-]	
Run 1	South	6	6	4	7	10	7	56.7	7	140	720
	East	6	6	4	8	10	1	60.3	6	120	
	North	6	6	4	7	10	1	58.6	7	140	
	West	6	6	4	10	7	9	58.4	6	120	
							Av.	58.5	Total	520	
Run 2	South	6	6	4	10	8	6	56.1	7	140	740
	East	6	6	4	7	9	9	62.6	8	160	
	North	6	6	4	7	8	3	60.5	6	120	
	West	6	6	4	1	3	1	60.3	5	100	
							Av.	59.9	Total	520	

Table 4
GA Results for the problem with seven parameters (Group B).

Group B	Orientation	P1	P2	P3	P4	P5	P6	P7	Q_{Total} [kWh/m^2]	# Gener. [-]	# Sim. [-]	Total simulation number
Run 1	South	6	6	4	1	8	1	5	52.3	52	1040	2220
	East	6	6	4	1	8	1	1	58.5	20	400	
	North	6	6	4	1	5	2	2	59.8	16	320	
	West	6	6	4	1	7	2	1	63.0	23	460	
								Av.	58.4	Total	2220	
Run 2	South	6	6	4	1	10	1	6	51.9	84	1680	3500
	East	6	6	4	1	8	1	1	58.5	35	700	
	North	6	6	4	1	3	4	1	59.9	42	840	
	West	3	6	4	3	7	1	13	69.4	14	280	
								Av.	59.9	Total	3500	

Table 5
AP Results for the problem with seven parameters (Group B).

Group B									Q_{Total}	# Gener.	# Sim.	Total simulation number
Step 1	Orientation	P1	P2	P3	P4	P5	P6	P7	[kWh/m^2]	[-]	[-]	
Run 1	All	6	6	4	1	9	4	13	64	11	220	
Run 2	All	6	6	4	3	2	2	11	68	13	260	
Step 2	Orientation	P1	P2	P3	P4	P5	P7	P6	[kWh/m^2]	[-]	[-]	
Run 1	South	6	6	4	1	7	1	11	52.5	9	180	820
	East	6	6	4	1	7	1	2	60.0	6	120	
	North	6	6	4	1	2	4	1	60.3	7	140	
	West	6	6	4	1	8	2	12	62.2	8	160	
								Av.	58.8	Total	600	
Run 2	South	6	6	4	1	5	1	12	52.7	8	160	780
	East	6	6	4	3	10	5	1	59.4	6	120	
	North	6	6	4	1	5	1	2	60.0	6	120	
	West	6	6	4	2	10	2	11	64.0	6	120	
								Av.	59.0	Total	520	

Computation time of AR

Depending on the version, for Group A, the AR needs 720 or 740 simulation runs, while the GA needs 2280 or 1640 simulation runs. The total simulation time is reduced by 62.8%. For Group B, the AR needs 780 or 820 simulation runs, while the GA needs 2220 or 3500 simulation runs. The total simulation time is reduced by 72.0%. All simulations are completed on a Win7 PC with Intel (R) Core (TM) i5 – 4590 CPU@ 3.30GHz and 4GB 1866 mhz RAM . It took about one and a half minutes for each simulation run (one minute for daylight simulation and half for thermal simulation). Therefore the AR took around 18 or 18.5 hours for Group A, and 19.5 or 20.5 hours for Group B, respectively.

These optimization results are shown to illustrate that the AR will largely reduce the computation time when compared with GA. This is mainly because that the AR finds the optimal glazing, insulation and infiltration with much shorter time in step 1, which are 200 simulation runs for Group A and 220 simulation runs for Group B. This largely reduces the simulation computation time in the next steps.

CONCLUSION

This paper proposed a new evolutionary optimization method – adaptive radiation, which is an improvement of genetic algorithms by largely reducing computation time in the optimization process. The efficiency in terms of robustness and computation time of AR is compared to the use of simple GA. Results demonstrated that implementation of AR can significantly reduce computation time than sole use of GA. The simulation time is reduced by 62.8% for Group A and 72.0% for Group B respectively.

The tendency toward a particular parameter setting, which can be found in all versions of the AR, suggests that the AR has the capability of finding a solution closed to the global optimum.

This method is reliable and efficient in the early design stage of architectural design, which can largely reduce the computation time and help make quick design decisions.

Optimizations for other climates in the United States will be implemented in the future to achieve the optimal façade solutions in different climates.

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