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Optimizing window system using genetic algorithm in a residential buildings in hot climate

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Abstract

Buildings consume about 40% of the annual world energy and 70% of the annual generated energy in some hot climate countries such as the State of Kuwait. Thus, building optimization is essential in such environment. Decomposing the simulation-based building optimization problem into dependent and interrelated component system such as window, lighting, and daylighting systems will reduce the handling computation time and results analysis. Such approach requires linking a building simulation program such as EnergyPlus with an evolutionary optimization algorithm, which in this research is Genetic Algorithm (GA).

A bedroom was selected on first floor of a residential building which has been rotated to face the four main directions (North, West, East, and South) . The optimization design parameters were window-to-wall-ratio (WWR), window and frame materials, overhang depth and inclination, room depth, and sided-fins depth. Such set of parameters with their bounds turned into about 8 million possible solutions. This defiantly requires high demand of computations. Thus, a server with 48 threads powered by 2 x Intel Xeon 2.5GHz with memory size of 64GB RDIMM was utilized.

The main objectives of changing the design parameters were set to minimize the energy consumption of the tested room as well as maximize the daylighting availability. The results showed a reduction on the zone consumption up to 32% relative to the base case. Also, the daylighting was ranging from 12-24 lux which relatively acceptable for such activity. Interestingly, the objectives have achieved with different varieties of the design parameters that give the architectures opportunity to select the preference layout design. This work can be further extended to analyze the cost effective of the optimum solutions.

Keywords - Evolutionary optimization algorithm, Genetic Algorithm (GA), window system, simulation-based building problem, window-to-wall-ratio (WWR)

Introduction

Over the past few decades, the building optimization discipline has gradually progressed as many other disciplines do. Before computer technology was readily available, and calculations were performed manually, researchers where restricted of optimizing only few variables such as window size, insulation, or building layout each on a time.

However, in the last two decades with the rapid evolution of computer technology the researchers have been focused on simulating and analyzing building performance using simulation programs that can behave similarly to an actual building performance. Also, the researchers have invoked many optimization algorithms that can be coupled with such simulation program. This integration is known as simulation-based building problem, to explore more efficient buildings. Some of these algorithms are able to efficiently handle large number of design variables, with or without constraints on the objective function.

Recent research has shown that building energy use can be reduced up to 32% by using simulation-based building optimization [1-2]; the 32% reduction being in relation to benchmark design energy use.

Simply, simulation-based optimization is coupling an optimization algorithm with a building simulation program such as the “state of the art” EnergyPlus [3]. The input parameters to the simulation program represent the building design, and control parameters. Simultaneous changing to these parameters will lead to different possible solutions. The search space (possible solutions) can be systematically searched by an optimization method.

The best algorithms that can match the characteristics of building optimization problems are the evolutionary algorithms (EAs) as recommended in the literatures. In particular, genetic algorithms (GAs) which have been found robust in finding the optimum solutions [2].

In the literature, the building optimization researches focused on partial building optimization such as envelope design and building construction [4]. Some others researches have been conducted for the whole building optimization problems including the construction and control operation [5-10]. However, none of these used simulation-based optimization techniques as a tool to find the efficient window system with different layouts.

Therefore, in this research, the main objectives are to minimize the energy consumption of the tested room as well as to maximize the daylighting availability. A high performance server (48 threads powered by 2 x Intel Xeon E5-2680v3 (12C, 2.5GHz) with memory size of 64GB RDIMM (8x8GB), 2133MT/s) will be used to manipulating the tremendous number of possible building solutions.

1. Simulation-based Building Optimization Problem

Optimizing any scientific problem requires an extensive evaluation of the objective function. In the case of building optimization problem, an extensive number of building parameters needed to be evaluated. This may be the real challenge in using simulation-based model. For instance, in this research 14 design parameters are assigned to be vary on different size step (bounds); this tuned into 8 millions of possible solutions. In practice, this will not be really convenient for a building designer, where the design may need to be changed several times in its primary stage until the client is satisfied. It is even more difficult for a researcher who wants to test different control parameters and may need to replicate each set more than once to ensure the accuracy of the results.

To overcome such an obstacle many approaches are suggested: a) using parallelized method through network, b) evaluated solution is saved in a database or virtual memory so as not to re-evaluate the similar solutions, c) simplifying the objective function and/or its constrained.

The most effective way of implementing these kinds of approaches in a building optimization problem is by minimizing the number of function calls (building simulation).

A. *Building Simulation Program*

In order to employ a simulation-based optimization; the optimization algorithm has to be coupled with a model that behaves in a similar way to a real building, such as EnergyPlus, BSIM, and DOE-2. The simulation program that has been selected to be coupled with the GA optimization algorithm in this research is EnergyPlus. This new-generation building energy simulation program (April, 2001), is the outcome of more than two decades of development by the U.S Department of Energy [11]. The U.S government supported the development of two building simulation programs: DOE-2 and BLAST. Each program contains hundreds of subroutines working together with different approaches to simulate the heat and mass flow throughout a building.

Fortunately, EnergyPlus combines the good features of DOE-2 and BLAST as well as its own new features. One of the major improvements of EnergyPlus over previous software is the integration between the building loads, system and plant. This feature allows accurate space temperature predictions using the Predictor-Corrector Method. This method predicts the mechanical system load needed to maintain the zone air set point and simulates the mechanical system to determine its actual capacity. Then, it recalculates the zone air-heat balance to determine the actual zone temperature. In addition, the EnergyPlus source code is well written and organized in such way that allows the user to easily modify and incorporate it.

Much research projects have validated the performance and accuracy of the EnergyPlus [12]. Their papers showed a close match between the measurement and the data predicted by EnergyPlus. This work and the validation of many other showed that the EnergyPlus could predict the building thermal performance with high accuracy. In this study, the program is used to calculate the heating, cooling, lighting, and equipment consumptions.

B. *Genetic Algorithm*

John Holland and his colleagues at the University of Michigan developed genetic algorithms (GAs). Their intelligent idea is explained in a book published in 1975 under the title of “Adaptation in Natural and Artificial System” [13] where they simply applied the natural genetic behavior of animals to artificial creatures. In natural law strong genes will survive for many generations. Similarly, in artificial creatures, a random set of chromosomes (population) is initiated first, and then an evolution to that initial population takes place, by means of reproduction operators: selection, crossover, and mutation. A selection operator is invoked to create a new intermediate population of parents, where the probability for each individual to survive is in linear proportion to its fitness value. Basically, above average individuals will be most likely to have more copies in the intermediate population, while below average individuals will be in a risk of being discarded. After the population of parents has been selected, a reproduction operator is applied to produce the new offspring.

Then a fine alteration to the new chromosomes is invoked by what is called a mutation operator. From the above description, the reproduction looping will keep continuing forever, forming an infinite loop. However, this process is terminated if one of the following four conditions is satisfied: a) a good solution is found, b) a certain number of generations or function calls have been reached, c) a set time has elapsed, or d) no improvement has taken place in the solution. This concept is illustrated in Fig. 1.

GA, historically, is encoded into binary strings where each design variable is represented by a binary bits according to its upper and lower bounds and their changing increment. The whole design variables are concatenated to form a binary chromosome.

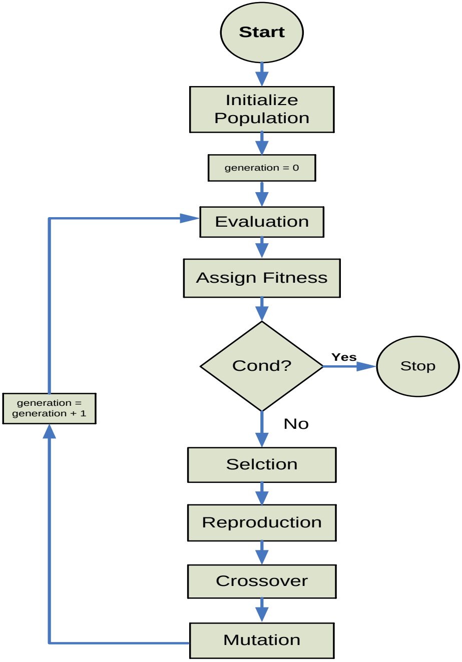

Fig. 1: Basic Genetic Algorithms (GAs) flowchart.

In this paper different population size have been tried to ensure the search not trapped on a local optima solutions. Ultimately, a GA of 60 population size with high reproduction rate, 100 % crossover and 10% mutation rate, were used for number of generations of 500. Such structure has proven to find optimum solution with relatively less number of simulation calls [14].

2. Building Example Description

A brief description of the building that going to be optimized will be described in the following sub-sections.

A. Building Geometry

The dimensions of the representative rooms of residential house in the State of Kuwait that used to determine optimum window system elements and combinations for the four main orientations are shown in Fig. 2.

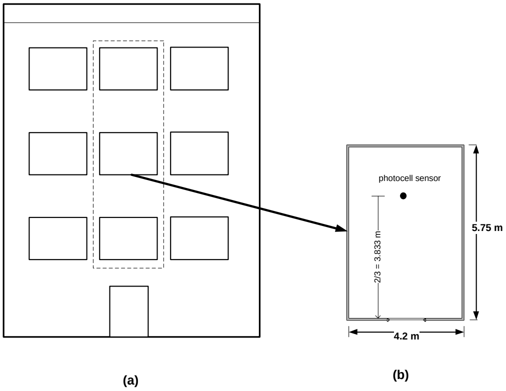

Fig. 2: Schematic of the house showing the representative rooms. (a) Front view of the house (b) Plan view of mid-floor bedroom.

B. Room Geometery

Typical bed and living rooms have been chosen to experiment the different elements of the window system. The bedroom is in mid-floor in multi-floor building; see Fig. 1.b. The front view of these rooms is shown in Fig. 3 without overhang. The zone area of the room is 24.15 m^2 (4.2m x 5.75m) and height of 3.5 m.

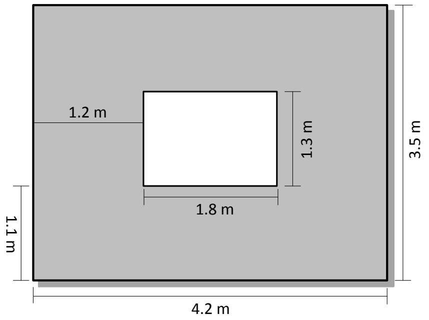

Fig. 3: Front view of the bedroom.

C. Local Weather Data

In this research, the weather data for Kuwait City, Kuwait (29.22° Latitude, 47.98° Longitude and 55m elevation) has been selected as the external environment of the simulated buildings. The design days of summer and winter seasons in Kuwait City, as per Energy Conservation Code of Practice (MEW-R-6, 2014), are shown in Table 1.

Table 1: Design days in Kuwait City, Kuwait.

Design Day	Dry-bulb temp. (°C)	Range of Dry-bulb Temberature (°C)	Humidity indicating temp. (°C)	Month/ Day
Summer	48	13	22	7/21
Winter	10.5	7	10	1/21

The data of these design days, together with the design supply temperatures, are used to automatically size the heating, ventilating, and air conditioning (HVAC) systems using EnergyPlus simulation program. However, the building response to the auto-sized HVAC system considered over a complete meteorological year, in order to accurately calculate the total building energy consumption. The indoor temperatures were set at 21°C and 24°C for the winter and summer respectively.

D. Building Internal Loads

Internal loads can generally be classified into two categories: constant and variable. The constant internal load, such as equipment and people, does not change with a changing environment, whilst the variable internal load, such as lights, should vary with the daylighting. In the considered room, an integration of photocell sensor that works to dim the artificial lighting as the natural light illuminance increases is selected.

The most common lighting system in Kuwait is fluorescent light with a lighting level of 7 W/m^2 as determined by the MEW R-6. The lighting type considered on the base case room is compact fluorescent of 0.37 fraction of radiant and 0.18 fraction visible and 0.45 convection fraction and the activity level was set to 70 W/person, see Table 2.

Table 2: Internal load of the building.

Internal Load Type	**Design Level**
People activity	70 W/person
Lighting	7 W/m²
Equipment	5 W/m²

The total heat gains of each kind of internal loads are calculated based on a 24 hour schedule. A fraction in each hour in the schedule is assigned to represent the percentage of the internal load presence. The schedule has been set to differ for weekday than weekends of occupants' presence.

E. Fenestration

Building fenestration is the weakest thermal point in building construction envelope. This is because it allows more heat to be transferred from/into the internal environment. For this reason more attention should be paid to this building element by the designer in the early design stage. Thus, different materials from the common practice to the most efficient were considered, see Table 3.

Table 3: Details of window materials specifications

Window materials specifications	Clear	Green	Bronze	Bronze	Low-e	Low-e
Thickness (mm)	6	6	3	6	3	6
Solar transmittance at normal incidence	0.85	0.48	0.6459	0.4856	0.1147	0.67
Visible transmittance at normal incidence	0.881	0.47	0.6797	0.5329	0.1170	0.8269
Thermal conductivity (W/m.K)	0.9	0.9	0.5780	0.5780	0.5780	0.5780

Generally, double-pane windows are widely recommended to be used in efficient or commercial buildings. For this reason, a double-pane window construction is allowed to be formed using any of the single glass material types described in Table 3. Also, two air spaces (6 mm and 12 mm) were used to fill the space between the window pans. The gas properties are provided by the building simulated energy program library (EnergyPlus).

Ultimately, in order to complete the fenestration component, the overhang has to be elaborated. The overhang and side fins were considered to cast a shadow over the attached surface. This helps to reduce the unwanted solar coming into the interior zone in certain time of the day by shadowing the window as shown in Fig. 4. The window's overhang, in this research, is set to be optional from zero depth from the wall base to the maximum possible depth (1.05 m) and sided-fins from zero to 0.75 m.

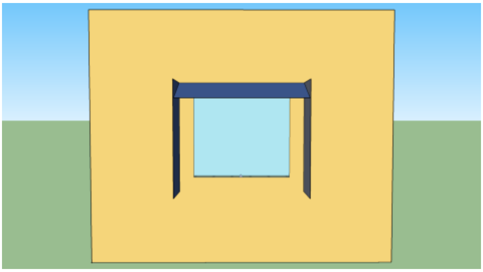

Fig. 4: Illustration for window's overhang.

3. Optimum Design Solutions

In this section the most effective optimum solutions of the selected multi-objective search space (minimize energy consumption and maximizing the daylighting) which is known as Pareto-front shown on red dots in Fig. 5, while the blue dots represent the last generation best solutions and the white dots represents the whole solutions where the energy consumption varies from about 2430 to over 5850 kWh with the window design. These large variations of energy consumption indicate the importance of optimization of window systems.

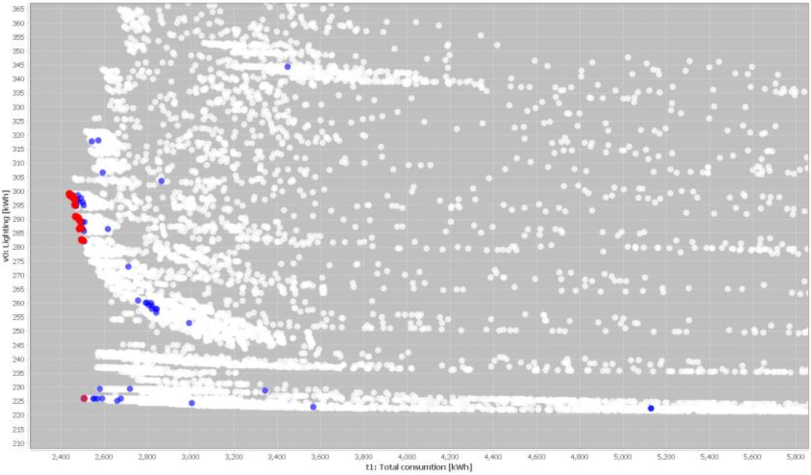

Figure 5: Optimum soloutions of the two main objective is shown in red doted.

The best solutions for all four orientations are listed in Table 4. Three solutions are provided for each orientation except for south where two solutions are listed. The base case is set as a window of aluminum frame, double pans of clear glass, and 6mm air gap without overhang or side fins. The base case is used to compare the energy saved due to application of best solution. The best solutions yield average energy consumption in the range of 2420-2518 KWh (4% variations) in all orientations. Windows of the best solutions are made of PVC frame with low-e glass of 3 or 6mm thickness and 12mm air gap. It is clear from the results that small window size is preferable since its WWR were ranging from 10-20% although its maximum bound was 90%. This is to limit the room expose to solar radiation of the sever summer climate. Also, the results provide effective construction dimensions of the window system such as width and height, overhang depth and its tilt angle along with the side fins. The reduction in energy consumption resulted from using the best solutions ranges from 16% for south orientation to over 30% for the other directions (North, East and West). It is to be noted that WWR of 20% saves energy consumption of about 30% compared to the base case with WWR of 15%, i.e. best solutions provide energy saving with higher WWR.

Table 4: Results of best solutions in the four directions.

	Depth	Overhang Depth (m)	Overhang Tilt (°)	Side Fin Projection (m)	Window Const.	Filling_Gas	WWR	Window Width	Window Height	Window Area	Frame and Divider Type	Light Intensity (Lux)	Total Cons. (Min.)	Total Cons. (Max.)	Total Cons (Avg.)	Energy Cons. Reduct.
West	4	0.65-1.05	120	0-0.75	Low-e3mmclear	12 mm air	10	1.3	1.1	1.5	PVC	12.6-13.7	2438.4	2455.9	2446.0	**31.3**
	4	0.55-1.05	90-120	0.1-0.75	Low-e3mmclear	12 mm air	15	1.6	1.4	2.2	PVC	15.2-20.6	2457.1	2485.6	2469.2	**30.7**
	4	0.75-1.05	115-120	0.1-0.75	Low-e3mmclear	12 mm air	20	1.9	1.6	2.9	PVC	22.6-26.2	2486.0	2502.3	2494.2	**30.0**
	4	**0**	**0**	**0**	**Double-Clear**	**6mm**	**15**	**1.8**	**1.3**	**2.34**	**Alum**	**533**		**Total**	**3561.24**	
East	4	0.65-1.05	120	0-0.75	Low-e3mmclear	12 mm air	10	1.328157	1.106797	1.47	PVC	12.1-12.9	2460.4	2477.6	2468.5	**31.0**
	4	0.55-1.05	110-120	0.15-0.75	Low-e3mmclear	12 mm air	15	1.626653	1.355544	2.205	PVC	15.1-18.8	2478.2	2508.7	2419.9	**32.4**
	4	0.75-1.05	120	0.25-0.75	Low-e3mmclear	12 mm air	20	1.878297	1.565248	2.94	PVC	20.3-23.3	2509.5	2528.1	2517.7	**29.6**
	4	**0**	**0**	**0**	**Double-Clear**	**6mm**	**15**	**1.8**	**1.3**	**2.34**	**Alum**	**518**		**Total**	**3578.03**	
South	4	0.55-1.05	110-120	0.15-0.75	Low-e3mmclear, Low-e6mm, and	12 mm air	10	1.3	1.1	1.5	PVC	9-239.8	2445.5	2699.1	2516.2	**16.0**
	4	0.45-1.05	115-120	0.2-0.76	Low-e3mmclear and Low-e6mm	12 mm air	15	1.6	1.4	2.2	PVC	10-272.6	2459.9	2744.5	2459.7	**17.9**
	4	**0**	**0**	**0**	**Double-Clear**	**6mm**	**15**	**1.8**	**1.3**	**2.34**	**Aum**	**184**		**Total**	**2996.3**	
North	4	0.65-1.05	115-120	0-0.75	Low-e3mmclear	12 mm air	10	1.3	1.1	1.5	PVC	12.1-12.9	2460.4	2477.6	2468.5	**31.0**
	4	0.55-1.05	115-120	0.15-0.75	Low-e3mmclear	12 mm air	15	1.6	1.4	2.2	PVC	15.1-18.8	2478.2	2508.7	2419.9	**32.4**
	4	0.75-1.05	115-120	0.25-0.75	Low-e3mmclear	12 mm air	20	1.9	1.6	2.9	PVC	20.3-23.3	2509.5	2528.1	2517.7	**29.6**
	4	**0**	**0**	**0**	**Double-Clear**	**6mm**	**15**	**1.8**	**1.3**	**2.34**	**Alum**	**184**		**Total**	**3612.1**	

It can be concluded from the above discussion that the building is affected by the climate conditions, building construction, and layout. However, optimum solutions can be achieved based on defined objective function, in this study was the zone energy consumption and daylighting. The results showed that efficient energy consumption can be achieved with variety of different construction and layout options.

4. Conclusion

Integrated EnergyPlus and Genetic Algorithm proves to be an effective building optimization technique which is capable of providing best solutions to such complicated problems while satisfying the stated objective function. The window system of a room in the middle floor is optimized in cases where the room is facing east, west, north or south direction under hot climate conditions. The best optimized solutions yield similar energy consumptions for the room while facing any of these directions with window-to-wall ratio (WWR) from 10-20% while the daylighting is kept at its maximum possible value (12-24 lux). Therefore, initial building layout can be optimized in all directions with variable WWR from 10-20% while saving energy up to 32%. These varieties of WWR are attained for different window specifications such as width, height, glazing types, air gap thickness, frame material, and window's overhang and sided-fin. This work can be extended to include the cost effective of each possible optimum solution.

Therefore, the findings of this study have provide a solution to the controversy between architectures and energy engineers as WWR up to 20% can be used while energy up to 32% may be saved. This gives the architectures options of selecting the appropriate façades layout without prejudicing the energy consumption of the building.

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