Maximizing Occupants Comfort in Affordable Housing Units

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ABSTRACT

Improving occupants comfort in affordable housing units has become a major priority in recent years to enhance the life-standards of their residents. Quantifying and maximizing occupants comfort in affordable housing units are dependent on design and construction decisions that affect the occupants' thermal comfort, indoor air quality, and daylighting quality. This paper presents the development of a model to assist decision-makers in optimizing the configurations of single-family housing design and construction decisions to maximize occupants' comfort in affordable housing units while complying with annual energy cost constraints. The model incorporates genetic algorithms that are linked to an external energy simulation program, *EnergyPlus*. A case study is analyzed to illustrate the practical implementation of the model and evaluate its performance.

1. INTRODUCTION

Low-income households in the US spend 20% of their average annual income on home energy costs while median income households spend 5% of their average annual income (NFFN et al. 2001). This highlights the need for affordable housing units that are capable of minimizing their annual energy consumption and cost while ensuring enhanced comfort for their residents (USGBC 2013). Occupants comfort in affordable housing units can be enhanced by improving the occupants' thermal comfort, indoor air quality, and daylighting quality of the housing unit (EPA and Office of Air Radiation 1991; Kibert 2005; Schenck et al. 2010).

A number of studies were conducted to investigate and study housing occupants comfort by focusing on improving: (1) the occupants thermal comfort (Magnier and Haghighat 2010; Wright et al. 2002), (2) indoor air quality (Lee et al. 2002; Schenck et al. 2010), and (3) daylighting quality in housing units (Joines 2009; Li et al. 1999; Tuhus-Dubrow and Krarti 2010). While these aforementioned studies have provided significant contributions to the area of improving occupants comfort, they are incapable of optimizing design and construction decisions to maximize the occupants comfort within a constrained annual energy cost to ensure the affordability of these housing units.

OBJECTIVE

The objective of this paper is to present the development of an optimization model for design and construction decisions for single-family affordable homes. The model is designed to maximize occupants comfort while complying with a specified annual energy cost. The model is developed in three major modules: (1) model formulation module that identifies all relevant criteria, metrics, decision variables, objectives, and constraints; (2) model implementation module that generates the maximum occupants comfort; and (3) performance evaluation module that carries out a practical implementation of the model to asses and improve its performance. The following sections present a brief description of these three major modules.

MODEL FORMULATION MODULE

The present model is formulated in four steps: (1) identifying criteria and metrics; (2) determining decision variables; (3) formulating optimization objective; and (4) identifying model constraints. First, the model is designed to identify all criteria and their corresponding metrics which have major influence on the occupants comfort. These criteria and metrics are identified as *thermal comfort* (T) criterion that quantifies the predicted percentage of dissatisfied (PPD) index (Fanger 1972), *indoor air quality* (*A*) criterion that indicates the availability of a set of indoor air quality design and construction decisions developed by EPA (2013), and *daylighting quality* (*D*) criterion that quantifies the annual average daylighting illuminance level (Birdsall et al. 1990; Li et al. 1999) of the housing unit. Second, the model incorporates a set of decision variables to evaluate and quantify the performances of identified criteria, as shown in Figure 1.

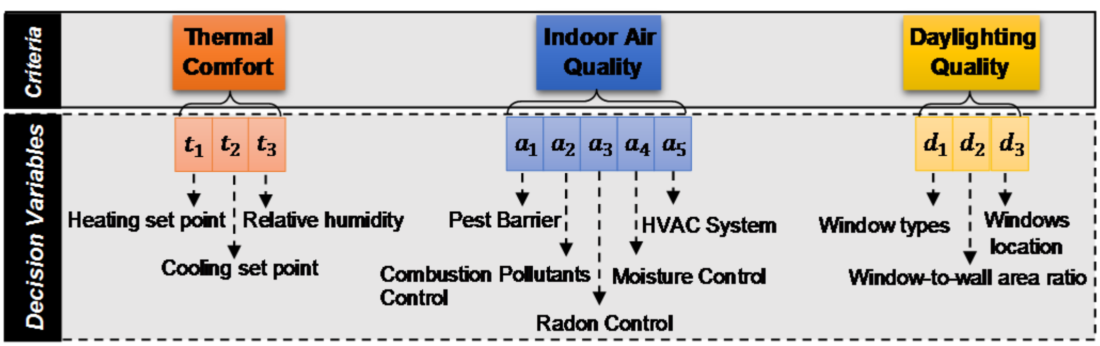

Figure 1: Model Criteria and Decision Variables

Third, the optimization objective of the model is developed to maximize occupants comfort index (*OC)* based on the weighted aggregation of '*TI*', '*AI*', and '*DI*' that represent the normalized performance of the thermal comfort (T) criterion, indoor air quality (A) criterion and daylighting quality (D) criterion, respectively, where '0' represents the worst and '1' represents the best OC performance (see Equation 1).

$$\text{Maximize OC} = (w_1 \times TI) + (w_2 \times AI) + (w_3 \times DI) \qquad (1)$$

Fourth, the model is designed to comply with all practical constraints including: (1) the types of decision variables of thermal comfort criterion (i.e. t_1, t_2, t_3), and daylighting quality metrics (i.e. d_1, d_2, d_3) are integer numbers; (2) the types of decision variables of indoor air quality criterion (i.e. a_1, a_2, a_3, a_4, a_5) are binary numbers; and (3) the annual energy cost (C^u) should not exceed a user-specified level and it depends on all identified decision variables ($t_1, t_2, t_3, a_1, \cdots, a_5, d_1, d_2, d_3$), and pre-defined housing features (X) such as wall insulation (see Equation 2).

$$\text{Minimize } C^u = c^u(t_1, t_2, t_3, a_1, \cdots, a_5, d_1, d_2, d_3, X) \qquad (2)$$

The present model is designed to interface with an external simulation program, *EnergyPlus*, to calculate the performances of the thermal comfort criterion (i.e. PPD index), the daylighting quality criterion (i.e. the annual average daylighting illuminance level), and the annual energy cost (C^u) of the housing unit.

MODEL IMPLEMENTATION

The optimization model was implemented using genetic algorithms GA (Goldberg 1989, Caldas and Norford 2003; Magnier and Haghighat 2010). The model was implemented using MATLAB 2012a and coupled with an external energy simulation program, *EnergyPlus* (2011). The model was implemented in three main steps: (1) input all relevant data to initialize the GA search process, (2) GA search process that executes the EnergyPlus and runs the GA to select the fittest solutions from calculated occupants comfort index (OC) within the specified annual energy cost (C^u); and (3) generates the optimum solutions and rank them based on the computed OC, as shown in Figure 2.

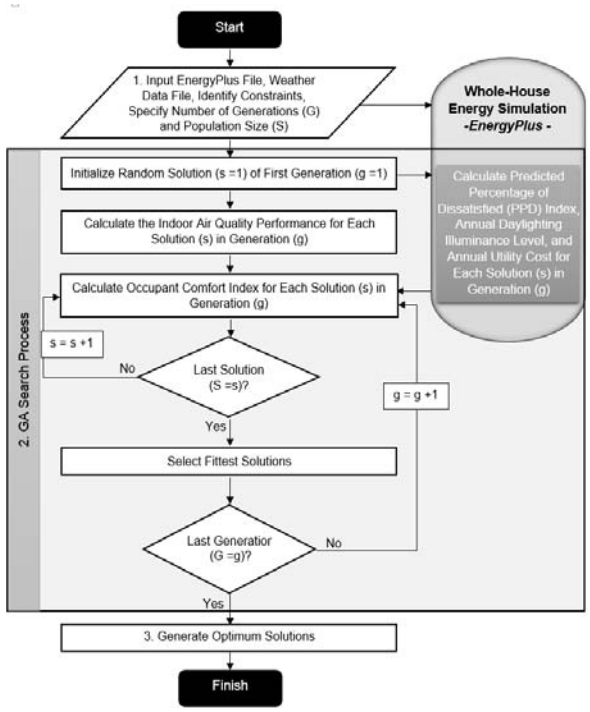

Figure 2: Model Implementation

PERFORMANCE EVALUATION

An example of a single-family housing unit was analyzed to illustrate and evaluate the capabilities of the developed model in various US locations. The application example housing unit was selected as the Building America B10 Benchmark house (2010), and designed as a one-story single-family housing unit covering an area of 1800 ft^2 with a garage. The weights of importance *(w)* for the criteria of occupants comfort were assigned as w_1=0.35; w_2=0.45; w_3=0.2. The application example was analyzed in three different US locations: Boston MA, Miami FL, and San Francisco CA. The annual energy cost constraint (C^u) for each US location was specified as: $1875, $1520, and $1545, respectively. Accordingly, the present model was able to compute the occupants comfort indices, OCs, to identify the optimal configurations of design and construction decisions for the analyzed housing unit in each selected US locations, using Equation 1.

The optimization results that achieve the maximum occupants comfort index (OC) for each selected US location were shown in Table 1. These results show that occupants comfort (OC) was majorly affected by the climate condition, where Boston in Cold/Very Cold, Miami in Hot-Humid and San Francisco in Marine climate regions based on the DOE (2013) climate zone map. Accordingly, occupants comfort were maximized within the specified annual energy cost (see Table 2) due to improving: (1) thermal comfort by maintaining the heating set point of 71F in cold/very cold climate conditions (i.e. Boston), and the cooling set point of 79F in in hot-humid climate conditions (i.e. Miami); (2) indoor air quality performance by ensuring the availability of all indoor air quality design and construction decisions (i.e. pest barrier, combustion pollutants, radon control, moisture control, and upgraded HVAC systems) in all selected locations; and (3) the occupants' exposure to daylighting by providing the window-to-wall area of 18% in San Francisco which has the mild climate condition. However, the window-to-wall area ratio was selected as 10% in Boston, and 12% in Miami in order to prevent the heat gain/loss through windows.

CONCLUSION

An optimization model was developed to assist decision makers in identifying optimal configurations of design and construction decisions for single-family affordable homes in order to maximize occupants comfort within a specified annual energy cost. The model was developed in three main modules: (a) identifying and incorporating all relevant criteria, metrics, decision variables, optimization objectives, and constraints; (b) implementing the model using genetic algorithm to generate the optimal solutions; and (c) evaluating and refining the performance of the model. An application example was analyzed in three different US cities. The results of this analysis illustrate the new capabilities of the developed model in generating optimal solutions for affordable housing units. These new and unique capabilities should prove useful to decision makers in Architecture/Engineering/Construction industry and is expected to improve occupants comfort in affordable housing units.

Table 1: Maximum Occupants Comfort Index for Each Location

Location	Boston	Miami	San Francisco
Max OC	0.73	0.83	0.80

Table 2: Optimal Solutions for Each Location

Criteria	Decision Variables	Optimal Solutions		
		Boston	Miami	San Francisco
1. TC	Heating set point (t_1)	71F	67F	67F
	Cooling set point (t_2)	81F	79F	80F
	Humidity percentage (t_3)	60%	55%	60%
2. AI	Pest Barrier (d_1)	Available	Available	Available
	Combustion Pollutants Control (d_2)	Available	Available	Available
	Radon Control (d_3)	Available	Available	Available
	Moisture Control (d_4)	Available	Available	Available
	HVAC System (d_5)	Available	Available	Available
3. DI	Window type (d_1)	High-solar-gain, [U-value: 2.2; SHGC: 0.53]	Low-solar-gain, [U-value: 1.4; SHGC: 0.3]	Moderate-solar-gain, [U-value: 1.5; SHGC: 0.44]
	Window-to-wall area ratio (d_2)	10%	12%	18%
	Location of windows (d_3)	3.6 ft[1]	3.2 ft[1]	3.6 ft[1]

[1]Elevation of windows from the ground

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