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Simulation Based Energy Control and Comfort Management in Buildings Using Multi-Objective Optimization Routine

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Abstract
Building energy management systems with high-level of sophistication have to control and manage a large set of actuators and other equipment and evaluate performance of each and every-subsystem on periodic basis. In the present study, a control algorithm has been developed as an engineered solution for intelligent energy control and comfort management in buildings. A hybrid genetic algorithm - particle swarm optimization based multi-objective optimization routine is developed to compute the optimal set-point level of heating, ventilation, and air conditioning and lighting systems with a view to balancing energy consumption and occupants' comfort. Occupants' comfort is evaluated for indoor air quality as CO_2 concentration, thermal and visual comfort. Case studies with a different set of optimal parameters have been worked out to calculate the amount of energy consumed as well as comfort level achieved. Overall occupants' comfort was improved by 17% and daily, weekly and monthly building energy consumption was reduced by 2.5%, 7.7%, and 17.9%, respectively. The developed intelligent control strategy can be integrated with building automation systems to achieve finely tuned real-time optimized comfort management

Keywords- Building energy model, Multi-objective optimization, Genetic algorithm, Particle swarm optimization, Pareto-front, Occupancy, comfort.

1. Introduction

Energy management issues in buildings' sector are not trivial and technological solutions for energy control and occupants comfort management are available (Kan et al., 2016a; Ngarambe et al., 2020). Such solutions have mostly led to failure of Heating, Ventilation, and Air conditioning (HVAC) systems due to poor execution of control algorithms (Shaikh et al., 2016; Li and Wang, 2020). Building service managers treat such failures through exhaustive maintenance and commissioning schedules. These exercises have been able to solve failure problems with satisfactory results but with increased operating and capital costs (Kan et al., 2016b; Ahmad and Khan, 2020). Thus, there is a need for an engineered solution that could effectively assist in energy control and occupants' comfort management in buildings.

Managing comfort in buildings with reduced consumption of energy starts early from design and construction stage. Reduction in window size, adopting small openings to ensure cross ventilation, and sparing the ventilation facilities, etc. have been adopted for the purpose of energy saving and ensuring comfort during 1970s and 1980s (Pérez-Lombard et al., 2011). Although, such measures reduced a small amount of cooling load required for HVAC systems and the amount of energy consumed but the comfort considerations of the occupants' were jeopardized (Chen et al., 2016).

Several design measures like daylighting, passive solar heating, and wireless sensor networks, etc have been adopted but most of them being site specific, were not effective in alleviating the contradiction between energy consumption and occupants' comfort (Harish and Kumar, 2021).

Equipment, appliance or any machinery that consumes energy and the processes that account for energy transfer within the building under study and also, with the external environment are regarded as building energy systems (Harish and Kumar, 2016a; Harish and Kumar, 2016b; Harish and Kumar, 2019). Such systems with appropriate control strategies vary the set-points of the physical building energy systems to provide appropriate comfort in terms of thermal and visual to the buildings' occupants. Several researchers around the world have developed building energy management system and control strategies with advanced controllers (Harish and Kumar, 2014; Khan et al., 2017). Such strategies are responsible in minimizing net energy consumption by the HVAC system, thereby reducing demand on the power grid. Systems, primarily responsible for thermo-visual comfort of occupants in a building are HVAC and lighting systems (US DOE, 2012).

2. Building Energy Model

To implement the developed control strategy a white-box model of a building energy system is developed based on the first principles of building physics. Parameters influencing transfer of energy through the developed white-box model are illustrated in Table 1.

Table 1. Significant parameters used to develop white-box model

Category	Parameters	Units
Environmental	Outdoor air temperature (T_{out}),	*°C* or *°K*
	Relative humidity (RH_{out}),	p.u. or percent
	wind speed (v_{wind}) and direction,	*m/s*
	solar radiation (H_{out})	W/m^2
Building envelope	Thermo-physical properties of construction elements (L, ρ, k, c_p),	m, kg/m^3, *W/(m·°K)* or *W/(m·°C)*, *J/(kg·°K)*
	Building orientation, planning and design specifications	
Occupancy factors	Causal heat gains (internal heat loads),	*W*, p.u.
	Functional use of building, and	
	Occupancy schedule.	
HVAC Plant	Plant heat rate,	*W*
	Number of ventilated air changes per hour,	h^{-1}
	Mass flow rate and temperature of coolant and	*kg/s*, *°C* or *°K*
	Valve signal	

In order to maintain appreciable accuracy, thermal energy transfer processes occurring within the building space and with exterior environment are considered as a combination of conduction and convection heat transfer. Heat conduction and convection equations (which are nonlinear in nature) are linearized using state space modelling approach. Representing a building energy system model using as state-space equations, enables to view the behaviour of outputs as a relationship to a set of inputs. This enables a modeller to better understand the system dynamics and behaviour (Gouda et al., 2002). Occupancy is considered to have active role in contributing to the cooling load calculation of the HVAC system along with other systems such as lighting, computers, refrigerators and like-wise. Such a heat gain is represented as causal heat factors for simplicity. Simulations are performed for a complete building space whose construction elements are chosen as per American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook of fundamentals, 2013 (ASHRAE, 2013). Three-dimensional schematic of a developed building energy model test case is shown in Figure 1.

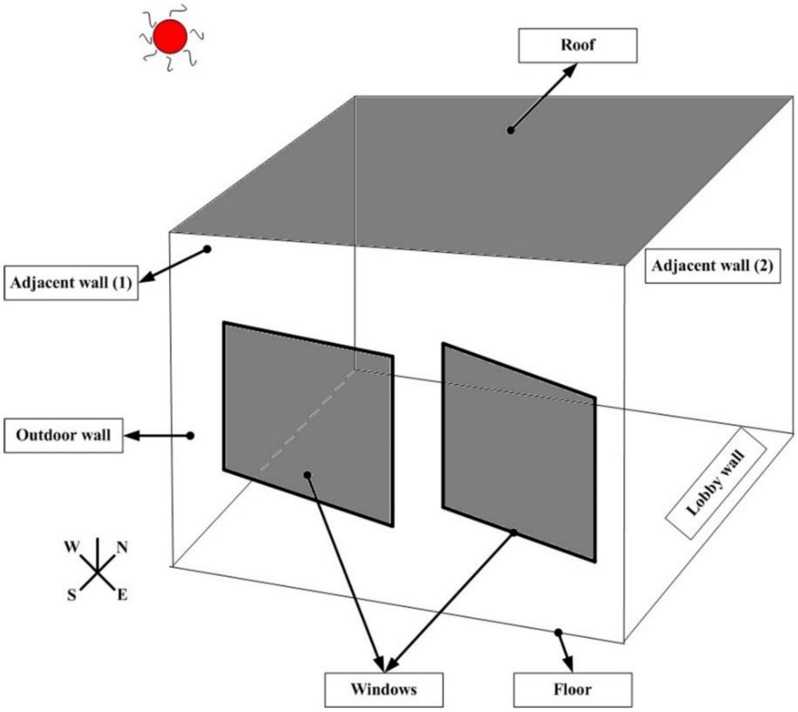

Figure 1. Building elements of the test case scenario

Developing a white box building energy model has its own merits and de-merits. Developed model is the most accurate model but lacks computational efficiency when a control strategy needs to be applied to the same model. In order to improve the computational efficiency in terms of the simulation time and speed, an optimization algorithm is applied to reduce the order of the developed white-box building energy model (Harish and Kumar, 2016c). White-box model is subjected to a step test input and the output results are recorded. Then the reduced order model is applied with the same test input and by using guess values of the reduced order model parameters, output is recorded. Error obtained in the outputs of both the before-mentioned cases are evaluated and used as a minimization index to identify the parameters of the computationally efficient building energy system model. Sum-squared error of both the responses is minimized to estimate the numerical values of the parameters of reduced order model.

3. Problem Formulation

Multi objective optimization problem for intelligent energy control and comfort management is given as (1) and (2). Overall comfort for occupants' is given as (1).

Maximize:

$$F_{comf}\left(T_{room},\mathrm{L}_{room},\mathrm{C}_{room}\right)=\lambda_T\left(1-\left\{\frac{\Delta T}{T_{sp}}\right\}^2\right)+\lambda_L\left(1-\left\{\frac{\Delta L}{L_{sp}}\right\}^2\right)+\lambda_C\left(1-\left\{\frac{\Delta C}{C_{sp}}\right\}^2\right) \tag{1}$$

where,

$F_{Comf}(T_{room}, L_{room}, C_{room})$	Overall comfort function of building's occupants,
T_{room}	Optimal building space temperature, °*C*,
L_{room}	Optimal building space illumination level, *lux*,
C_{room}	Optimal CO_2 concentration of air in the building space, *ppm*,
λ_T, λ_L, and λ_C	Allocating factors corresponding to thermal, visual and indoor air comfort, respectively,
ΔT	T_{room} - T_{SP} ,
ΔL	L_{room} - L_{SP} ,
ΔC	C_{room} - C_{SP} ,
T_{SP}	Occupants-defined set point values of building space air temperature, °*C*,
L_{SP}	Occupants-defined set point values of building illumination level, *lux*, and
C_{SP}	Occupants-defined set point values of building CO_2 concentration, *ppm*.

Minimize:

$$F_{energy}\left(P_{HVAC}, P_{light}\right) = P_T\left(T_{room}\right) + P_L\left(L_{room}\right) + P_C\left(C_{room}\right) \tag{2}$$

where,

F_{energy} (P_{HVAC}, P_{light})	Energy consumption calculation for the building energy system model under study,
P_{HVAC}	Energy consumed by the HVAC system to maintain set point temperature and humidity level, *W-h*, and
P_{light}	Energy consumed by lighting system to maintain set point illumination level, *W-h*.
$P_T(T_{room})$	Amount of energy consumed to improve building space air temperature from T_i to T_{Opt}, *W-h*,
$P_{light}(L_{room})$	Amount of energy consumed to improve building space illumination level from L_i to L_{Opt}, *W-h*, and
$P_C(C_{room})$	Amount of energy consumed to improve building space CO_2 concentration from C_i to C_{Opt}, *W-h*
T_i	Initial building space air temperature, °*C*,
L_i	Initial building space illumination level *lux*, and
C_i	Initial building space CO_2 concentration before applying intelligent BEC-CM, *ppm*.

$P_T(T_{room})$ and $P_C(C_{room})$ correspond to the energy consumed by HVAC system under study and is dependent on building space temperature, (T_{BS}) and relative humidity, (RH_{BS}). $P_L(L_{room})$ corresponds to the energy consumed by the lighting system. The objective functions of optimization problem for present study are (1) and (2) subjected to constraints in (3) – (6).

$$\lambda_T + \lambda_L + \lambda_C = 1 \tag{1}$$

$$0 \leq \lambda_T \leq 1,\ 0 \leq \lambda_L \leq 1,\ 0 \leq \lambda_C \leq 1 \tag{2}$$

$$20 \le T_{room} \le 24,\ 600 \le C_{room} \le 1000,\ 300 \le L_{room} \le 800, \tag{3}$$

$$P_{Tot} = P_{HVAC} + P_{light} > 0 \tag{4}$$

Constraints of eqn. (3) - (4) illustrate the bounds of the allocating factors used in the multi-objective optimization problem. Constraint represented by Eqn (5) represents the upper and lower bounds of all the decision variables of eqn. (1) and (2). Eqn. (6) describes the total power consumed by the building energy systems is summation of HVAC and lighting system power.

4. Solution Technique

A hybrid Genetic Algorithm (GA) – Particle Swarm Optimization (PSO) algorithm has been developed to solve the multi objective optimization problem; enabling optimal control for intelligent energy control and comfort strategy. Functions and operations of GA like mutation, traditional or classical crossover, and multiple-crossover and of PSO are used to develop a hybrid GA-PSO algorithm. Fuzzy probability is used for selection of these operators.

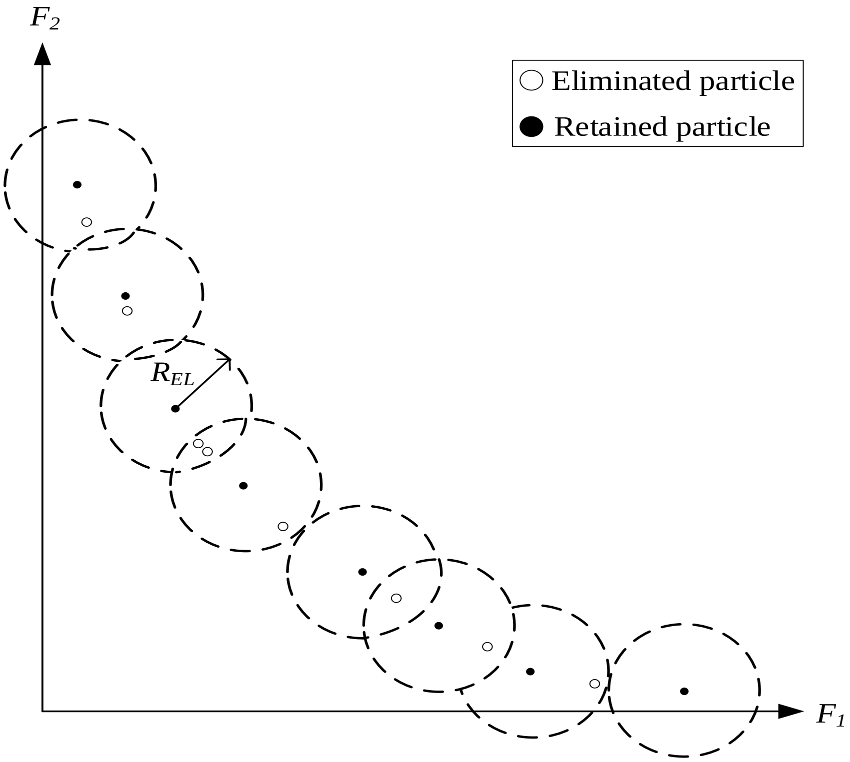

Figure 2. Dynamic elimination technique adopted for hybrid GA-PSO solution

Each particle of PSO operator has a set of different leaders and out of them one is chosen as a leader. A parameter called neighborhood radius (R_{NH}) is defined, to compute the number of neighbors of each non-dominated solution in the objective function domain. Based upon R_{NH}, particles with lower number of neighbors are selected as leaders. Then, the personal best position vector ($\vec{x}_{pbest_i}$) is the particle which is nearest member of the archive. Fitness values for each member of randomly generated population are calculated to produce the first archive. W, C_1, C_2, P_m, P_C, and P_{MC} are computed at every iteration. P_m, P_C, and P_{MC} are used to change randomly selected chromosomes. A group of chromosomes is then regarded as a '*swarm*' with each chromosome being represented as an individual particle. Also, chromosomes which are not being considered for GA operation are enhanced by PSO. The archive is then pruned using dynamic elimination approach and updated. A parameter called elimination radius (R_{EL}) is used to eliminate one of the two particles, by comparing Euclidean distance between the particles with R_{EL}. Use of dynamic elimination technique is illustrated in Figure 2.

This completes one iterative cycle and the iterations continue until a satisficing solution is obtained. Flowchart for the GA-PSO based multi objective optimization technique is shown in Figure 3.

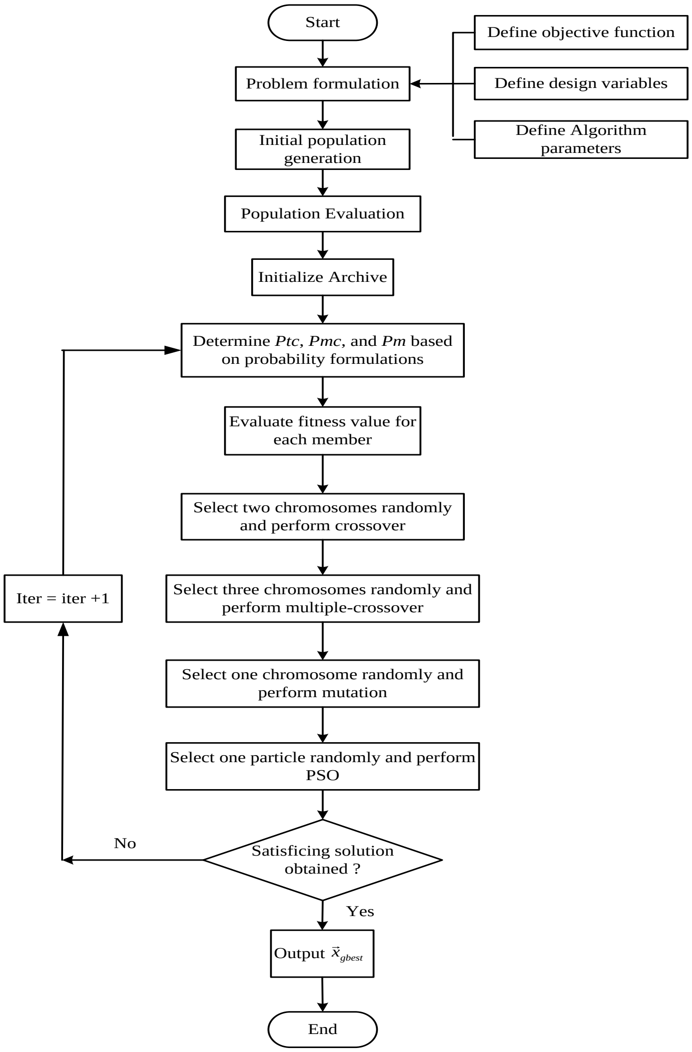

Figure 3. GA-PSO based multi objective optimization flowchart

Hybrid GA-PSO based multi objective optimization algorithm is implemented to building energy system for intelligent energy control and comfort strategy. On solving the developed multi objective optimization problem using hybrid GA-PSO algorithm, a Pareto front is obtained as shown in Figure 4.

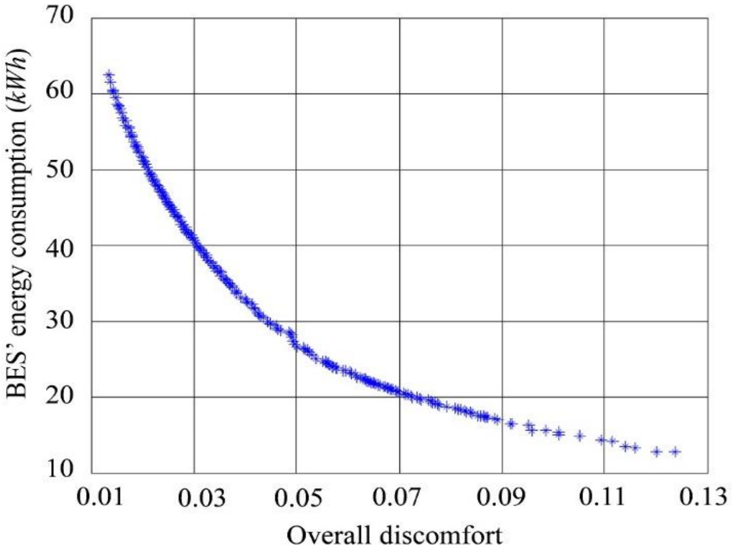

Figure 4. Pareto-optimal front of energy consumption versus overall dis-comfort

A multi objective optimization problem presents Pareto-optimal points with a pool of sample solutions and one set of solution points can be selected on the basis of buildings' functionality and occupants' preference. Few sample solutions out of the pool is illustrated in Table 2.

Table 2. Solutions with optimal values of decision variables

T_{room} (°C)	L_{room} (lux)	C_{room} (ppm)	Comfort	E_{Tot} (kWh)
23.18	783.14	683.25	0.9895	64.85
22.92	752.56	712.63	0.9974	64.62
22.41	612.73	756.18	0.9917	62.25
21.88	572.22	796.97	0.9904	60.89
21.12	539.14	808.12	0.9586	46.86
21.0	445.18	825.49	0.9485	45.73
20.58	417.25	925.91	0.9441	25.09

5. Conclusion

A hybrid GA-PSO based strategy for effective energy control and comfort management of buildings has been developed. Developed control strategy achieves improved comfort and decreased energy consumption of building energy systems. Occupants' comfort is evaluated for indoor air quality as CO_2 concentration, thermal and visual comfort. Case studies with different set of optimal parameters have been worked out to calculate the amount of energy consumed as well as comfort level achieved. Developed intelligent energy control and comfort management strategy is flexible for incorporation of new constraints based on occupants' preference. For instance, where reduction of energy consumption is a priority, the energy and comfort manager of building can choose an optimal point (T_{room}, L_{room}, C_{room}) from the pool of solutions which shall have minimum total energy consumption value and vice-versa.

Maximum comfort of occupants' is achieved at building space air temperature of 23.8°C, lighting of 783.14 lux level and CO_2 concentration of 683.25 ppm with overall energy consumption of 44.85 kWh. A significant reduction of 23.8% of energy was achieved as compared to PID controlled HVAC system.

Overall occupants' comfort was improved by 19% under low or zero occupancy periods and by 17% under full occupancy periods of time. Daily, weekly and monthly consumption of energy by HVAC and lighting systems of building energy system under study was reduced by 2.5%, 7.7% and 17.9%, respectively compared to PID controlled HVAC system. Developed intelligent control strategy can be integrated with building automation systems to achieve finely tuned real time optimized comfort management.

Conflict of Interest

No conflict of interest to be declared by the authors.

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