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Multi-zone Building Energy and Comfort Management using Computational Intelligence Approach

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***Abstract*: Smart buildings are a trend of next-generation's buildings, which allow people to enjoy more convenience, comfort and energy savings. One of the most important challenges on smart and energy-efficient buildings is to minimize the building energy consumption without compromising human comfort. This study proposes a multi-zone building control system coupled with an intelligent optimizer for effective energy and comfort management. Hybrid metaheuristic algorithm is utilized to optimize the overall system and enhance the intelligent control of the building in multiple zones. Experimental results and comparisons with other approaches demonstrate the overall performance and potential benefits of the proposed system.**

Keywords*: *Smart buildings, comfort management, multi-zone building control, optimization.

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I. Introduction

Smart and green buildings have recently become a trend for future building industry. From the perspective of system control, a smart and green building is a large-scale highly complexity dynamic system with the automation of building operations, maintenance and management. The sustainability of the energy efficient performance standards throughout the operating cycle is challenging. It is becoming apparent that cutting-edge technologies and latest innovation have the capacity to significantly improve the sustainable performance with human comfort and productivity [1-5]. The quality of life in buildings (comfort conditions) is mainly determined by three basic factors: thermal comfort, visual comfort, and indoor air quality [5-8]. Intelligent control of the thermal comfort, visual comfort and air quality comfort are important for both energy efficiency and occupants' quality of living. Several building energy management systems and techniques have been developed and a number of studies have been conducted in [6-9] for modern intelligent control systems for buildings. Multiple sensors in a building can be considered as an aggregation of interconnected things, gateways or controllers, for achieving some global objectives to meet the requirement of environmental friendliness, the high-level comfort and the high energy efficiency. However, the effective operation of these systems is exceptionally difficult because external and internal building conditions change in a highly dynamic manner. Such changes include occupancy, weather, energy consumption and etc. Additionally, building operations are complex because a large number of constraints must be satisfied in order to ensure appropriate equipment performance and fulfill the comfort level. In particular, the control of energy and comfort management becomes more challenging for building systems since multiple distributed resources need to be effectively coordinated. The basic control objective for the multi-agent control system is to sustain the occupant comfort level while minimizing the energy consumption. Such problems are computationally intractable by conventional deterministic search algorithms. A smart building has to take into account the environmental factors that may affect human comfort, well-being and productivity. Thermal comfort in a room is determined by the indoor temperature and can be measured using temperature sensors. Illumination level can be taken as an index for visual comfort control. Indoor air quality can be improved by the ventilation system and generally the carbon dioxide concentration serves as an index for measuring the indoor air quality. A building is characterized as a network of zones in a multi-zone building. A zone defines an air volume in which the space shares uniform environmental conditions. The improvement of the indoor environment comfort demands more energy consumption and the building operations require high energy efficiency to reduce energy consumption.

One of the most challenging issues on energy-efficient buildings is to optimize the requirements of the human comfort and power consumption effectively. Finding the optimal solution is another key issue. There are several objectives to be considered simultaneously during optimization. It is normal that these objectives are conflicting in nature and finding an optimal solution involves trade-off among the objectives. The conventional point-by-point approaches for optimization are not appropriate for solving multi-objective optimization problems as the outcome of these classical optimization methods is a single optimal solution. That is, a weighted sum method would convert a multi-objective optimization problem into a single objective optimization. In order to make sure that every weight combination has been utilized, the algorithms are required to be executed iteratively. Conventional optimization methods have to start from initial guesses of optimal variables and their convergence speed is affected by their initial guesses in most cases. Apparently, this is not a feasible way to reiterate the algorithm continually as it would exhaust all the weight combinations. Hence it is essential for the algorithms to gather information from previous performance so as to target the appropriate range of weights in further evolutions. An overview of Population-based optimization techniques and the methodologies used for multiple objective problems is discussed in [10].

In this paper, a multi-zone building system with intelligent optimizer is proposed to control the building effectively in order to achieve high energy efficiency and human comfort. The focus of the optimization process pertains to the investigation on Memetic intelligence approach [11]. By making use of memetic approach, the problem can be scaled up, able to deal with large-scale multi-objective optimization for buildings. Memetic intelligence approach represents a synergy of evolutionary or population-based approach with separate local advance procedures for problem search and have been demonstrated to converge to high quality solutions more efficiently than their conventional counterparts (for e.g., genetic algorithm, ant colony optimization and etc.) on a wide range of real world problems. The flexibility of such an approach is evident when one has to further undertake resource allocation to multiple zones basing on the overall solution attained by the algorithm. With proper and domain-specific representation, the proposed approach can be effectively applied to achieve the overall optimization goal.

The rest of the paper is organized as follows. Details on the formulation of the problem are presented in Section II. Section III and Section IV present the solution and implementation, respectively, of the proposed approach substantiated with simulation results. Section V shows the results compared with the existing approach with brief discussions. It demonstrates that by using the proposed approach, the energy consumption is reduced while the occupants' comfort level is maintained at the steady state. Lastly, we summarize the main contributions of this study in Section VI, and enlist several recommendations for the future research.

II. Framework Architecture

The framework's general philosophy is presented in Fig. 1. This framework provides a foundation for seamlessly and securely connecting devices, delivering trusted data to the cloud and delivering value through analytics. It involves a set of sensors, gateways to cloud services; organized and statistically analyzed data sets on the energy use in the buildings and their energy efficiency and economic performance. The data from building automation systems, including meters, I/O units and sensors transfer through master generator to the cloud. The sensors, cloud, and software applications are tightly integrated, giving the user a rich and powerful experience. The system processes data, providing averages, pick-load, statistics and graphs regarding energy consumption and economic impact. End users can access, control the system via a secured user interface and identify the weak points through real-time monitoring and comparisons of energy consumption profiles from different time periods. The system would send the command to the master generator in order to change the operation of individual units.

The proposed work aims to achieve the intelligent control of building towards efficient energy and environmental management. The optimization problem for building energy management can be formulated in terms of a energy cost function subject to constraints of the building operations. We consider the optimization problem with the objectives of minimizing the power consumption, maximizing the occupant comfort. The optimization problem is defined as follows:

$$F = \sum_{i=1}^{n} w(i) f(i) \qquad (1)$$

$$f(i) = \delta_1[1 - (\frac{e_T}{T_{set(i)}})^2] + \delta_2[1 - (\frac{e_L}{L_{set(i)}})^2] + \delta_3[1 - (\frac{e_A}{A_{set(i)}})^2] \qquad (2)$$

where F represents the overall occupant comfort level, w is the weighting coefficient for zone i; f represents the occupant comfort level for each zone, which falls into [0,1].

It is the control goal to be maximized; δ_1 , δ_2 and δ_3 are the users-defined factors, which indicate the importance of comfort factors. δ_1 , δ_2 and δ_3 fall into [0,1], and $\delta_1 + \delta_2 + \delta_3 = 1$. e is the difference between set point and actual sensor measurement; T_{set} , L_{set} and A_{set} are the set points of temperature, illumination and air quality, respectively. The goal of the optimization algorithm is to identify the optimal set of solutions. However, identifying the entire optimal set is practically impossible due to its size. In addition, for many problems, especially for combinatorial optimization problems, proof of solution optimality is computationally infeasible. Therefore, a practical approach to combinatorial optimization is to investigate a set of solutions that represent the optimal set within a given computational time limit. The optimization engine generates smart solutions that can sustain a high level comfort (based on the user's requirements) with minimal energy consumption. The proposed work aims to achieve the intelligent control of building towards efficient energy and environmental management. It provides user-friendly and interactive energy management solution with intelligent task scheduling generations using computational intelligence approach.

Figure 1. Framework's philosophy

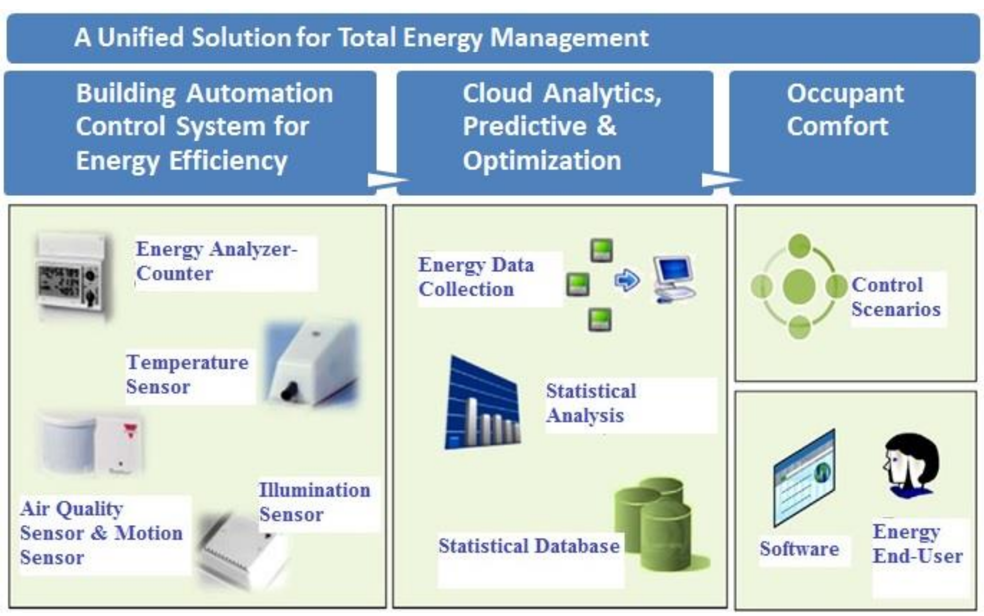


Figure 2. Frameworks of the multi-zone building control and comfort management system

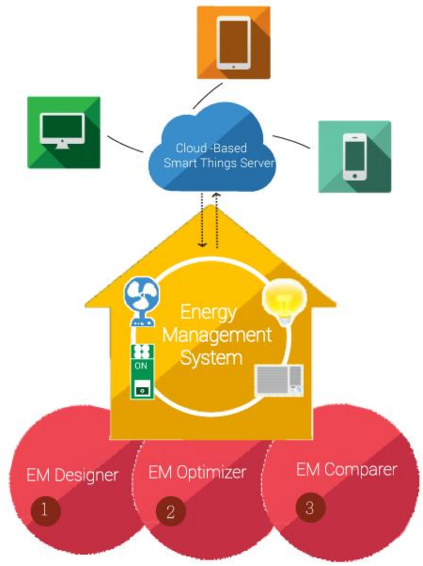


Figure 3. Architecture of the proposed framework

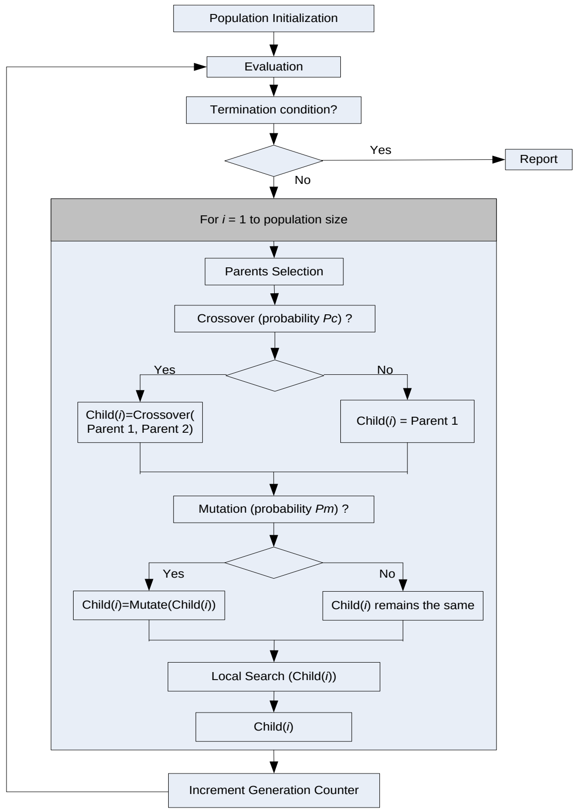
III. Solution Methodology

In the current work, the fundamental element in multi-agent control system is the agent, which can be software or physical entity. A hierarchical multiple agents-based control system is designed for building energy and human comfort management in the smart building. Fig.2 shows the overall system architecture. Based on the customer preferences and the set points predefined by the users, the multi-agent control system is utilized to reduce the error between the set points and sensor measured values so that the high comfort level is maintained and the energy consumption is reduced

The technology of multi-agent control system has been successfully utilized in various engineering fields.

A hierarchical multiple agents-based control system is designed for building energy and human comfort management in the smart building. Fig. 2 and Fig. 3 show the overall system architecture. The proposed framework consists of two elements which are server control engine (Energy Management System) and client control application (cloud server & mobile application). Users can access Energy Management System through cloud- based server with remote control functionality. The proposed framework consists of 3 parts: energy management designer, energy management optimizer and energy management comparer. Firstly, energy management designer allows users to design and customize their floor layout in the simulator; next, energy management optimizer made use of the new algorithm (as shown in Fig. 4) to generate the smart energy solutions in the form of task scheduling for multiple agents which can maintain HVAC (heating, ventilation and air-conditioning) in a higher occupant comfort level and energy efficiency than initial scheduling. Finally, energy management comparer provides the decision-making options that include the trade-offs by the comparisons of sensor values. Based on the occupant preferences and the set points predefined by the users, the multi-agent control system is utilized to reduce the error between the set points and sensor measured values so that the high comfort level is maintained and the energy consumption is reduced. The multi-agent control system is classified into different zone agents based on the distinct functions at multiple zones. The zone agents monitor the energy flow and responsible for energy management in its specific zone based on the occupant preference. The proposed algorithm is embedded in the master agent to optimize the set points. Multiple control agents are used to control the devices which are related to the comfort factors. The main comfort factors considered in this study include environmental temperature, illumination level and indoor air quality. Accordingly, the control agents are classified into the temperature control agent, the illumination control agent, and the air-quality control agent. Through the cooperation of these multiple agents, the overall goal can be realized.

Our focus is to develop a memetic computing algorithm for finding the optimum solutions. The solution of the optimization problem for a single building zone can be represented by an integer permutation. The proposed algorithm has a framework as shown in Fig. 4. After the population initialization, the population is evaluated and the termination condition is checked. If the termination condition is not met, the population is allowed to evolve further. In each generation, offspring is produced from the parent population through several genetic operators (crossover, mutation, and local search) and the population is replaced with the offspring. When the termination condition is met, the chromosome with the highest fitness value is returned which contains the sequence of set points for each zone. This sequence of set points represents the solutions for power distribution and the corresponding overall comfort.



Robust Memetic Algorithm
BEGIN
  Create an initial population of solutions $P(t=0) = \{s_1, s_2, \ldots, s_i, \ldots, s_M\}$
  For all $s \in P(t)$
    $s \leftarrow$ *individual-learning* (s)
  End For
  Individual Count $\leftarrow 0$
  While(stopping condition is not met)
    If $rand[0,1) \leq p_c$ **then**
      Select $s_i, s_j \in P(t)$
      $s_c \leftarrow$ *crossover* (s_i, s_j)
    Else
      Select $s_k \in P(t)$
      $s_c \leftarrow$ *mutate*(s_k)
    End If

    $s_c \leftarrow$ *split-repair* (s_c)
    $s_c \leftarrow$ *individual-learning* (s_c)
    $s_{worst} = \max_{s \in P(t)} C(s)$
    If $C(s_c) < C(s_{worst})$ **then**
      $P(t) \leftarrow P(t) \backslash s_{worst}$
      $P(t) \leftarrow P(t) \bigcup s_c$
    End If

    Individual Count $\leftarrow$ *Individual Count* $+1$
    If *Individual Count* $\geq M$
      Individual Count $\leftarrow 0$
      $t \leftarrow t+1$
    End If
  End While
END

Figure 4. Generic framework of the proposed algorithm

The generated algorithm represents the set points of the temperature, illumination and air quality by a integer permutation string. In the chromosome, each gene represents a set point in each time period for each building zone. The position within the string dictates the vector of power distribution to each zone. In the population evaluation, the objective/fitness function calculates the overall comfort (in the chromosome) in each time period by checking the connectivity between adjacent genes in linear time.

The goal of the solution is to achieve maximum comfort with minimal power supply. Utilizing the proposed Memetic approach, it aims to find the optimal solution for energy distribution to maximize the building's overall comfort. By way of example, we consider the multiple building zones with multiple agents portrayed in Fig. 5. Lastly, we demonstrate the efficiency and applicability of the proposed approach in the following sections.

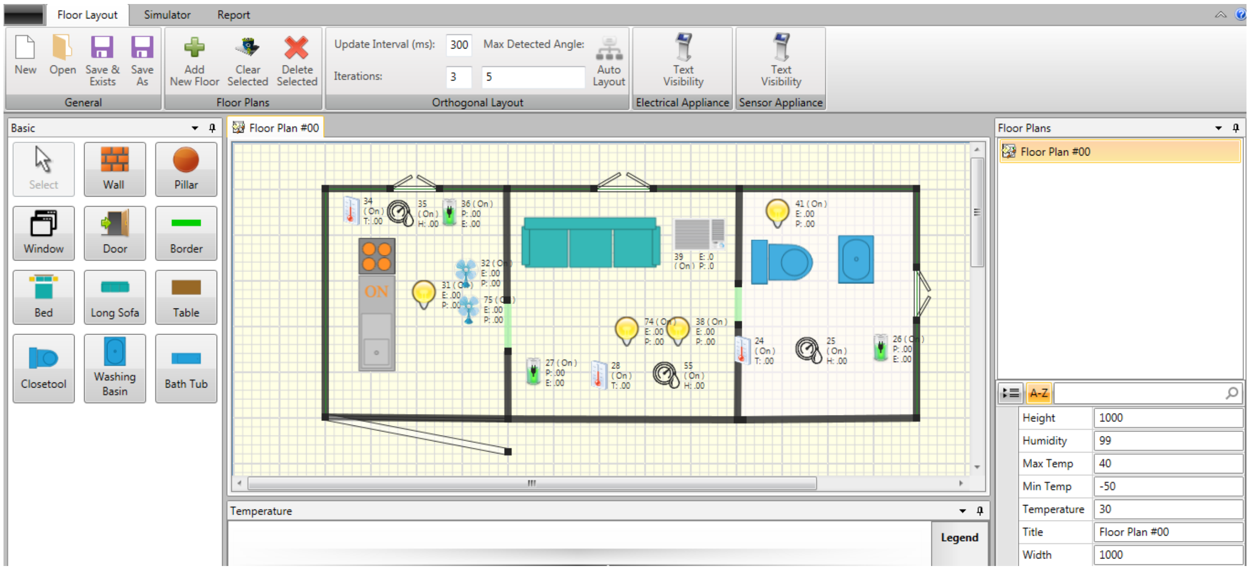


Figure 5. The multiple zones of a building

IV. Experimental Results

We apply our proposed approach by setting the initial population of the algorithm to 200 and specify the size of solutions as 200. We then run the algorithm for 500 iterations. The proposed approach was tested on a dataset with the weighting coefficients $w = \{0.3, 0.15, 0.05, 0.1, 0.1, 0.2, 0.1\}$ for seven building zones. Table I shows the experimental results of the simulation on these zones. The results were obtained in MS Windows 7 that ran on a PC Desktop with 2.60 GHz Intel i5-3320M CPU and 4GB RAM.

Zone	Avg. CPU Time (s)	Overall Comfort Factor
1	0.10	0.9785
2	0.11	0.9634
3	0.98	1
4	1.17	0.9907
5	1.43	0.9895
6	1.77	0.9563
7	1.97	0.9356

Table 1. Simulation results for the proposed approach for finding optimal solutions

In Table 1, it is shown that our proposed algorithm is able to uncover the optimal solution for 7 building zones within 2 seconds of computational time. To evaluate the performance of the proposed algorithm, it is essential to get a comparison on the performance of other existing algorithms with the proposed algorithm. Therefore in the simulation, the same dataset was tested using the existing algorithms. The existing algorithms include Tabu Search, Ant System were developed and tested against the same set of data. The algorithms were designed such that they share the same objective function as that of the proposed algorithm. Since these two algorithms were neighborhood search algorithms, they were designed to have similar class structure and methods. Both neighborhood search algorithms deploy two gene swapping technique and obtain the new neighborhood solution by selecting the best in the neighborhood of the current solution. In the Tabu search algorithm, the recency tabu table use a randomly variable tabu tenure size for diversification and the aspiration function bypasses the tabu for tabu move steps that outperform the current solution (i.e. the solution has a higher objective value than the current solution). The ACO algorithm was designed to have 200 ants uniformly distributed. Fig. 6 shows the plot of the performance of the algorithms in terms of the optimum solutions obtained and the time spent. It is observed in Fig. 6 that ACO lag behind both Tabu search and the proposed algorithms in terms of the time spent to find the solutions with maximal occupant comfort.

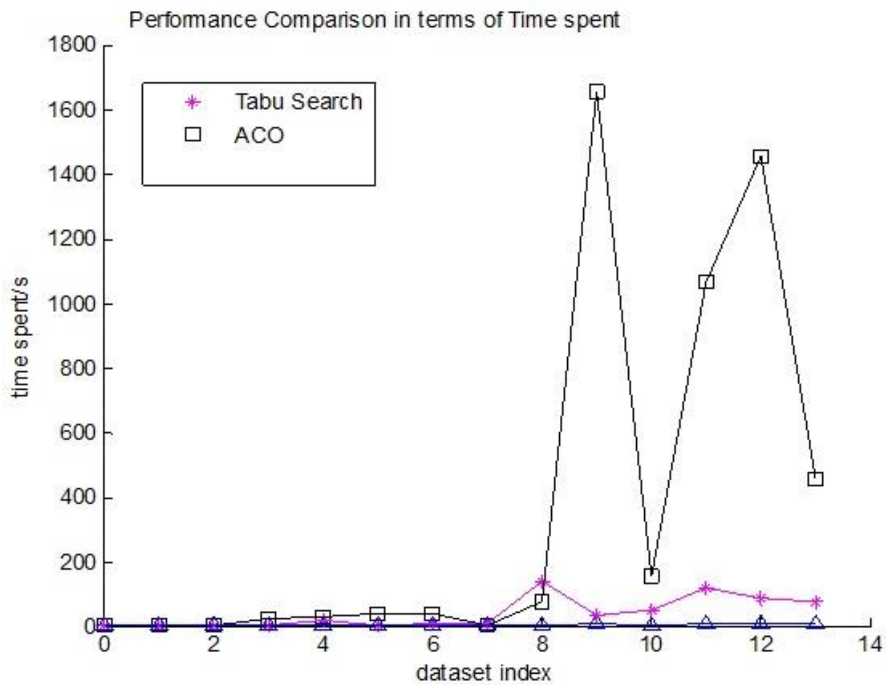


Figure 6. Comparison of the proposed algorithm (Δ) against Tabu search and ACO in terms of the time spent in obtaining the maximal occupant comfort

V. Results and Discussion

To demonstrate the efficiency and applicability of the proposed approach, we consider the multiple building zones with multiple agents as shown in Fig. 5. For simplicity, we set the same set points for the zones. The desired temperature is set as 30 ℃ and the set point for humidity is set as 80. The simulation results with and without the implementation of the proposed algorithm are illustrated in the following figures. As shown in Fig. 7 and Fig.8, the total energy consumption is around 100 with the initial schedule generated randomly, while with the optimized schedule generated through our proposed algorithm, the measured power consumption is significantly reduced to around 60.

Next, we perform further comparisons on the measured temperature and humidity before and after the optimization. The optimized schedule helps to reduce the power consumption while maintaining the desired temperature and humidity. After the optimization process, several solutions will be generated which could be better than the initial schedule or worse than the initial one. But certainly, the optimized schedule will be able to maintain the temperature and humidity at certain comfort level, which can be justified through the comparison between Fig. 9 and Fig. 10, and the comparison between Fig. 11 and Fig. 12. It is worth noting that with the proposed algorithm, the temperature and humidity can achieve the desired set points much faster, and then be able to maintain the values at the steady state.

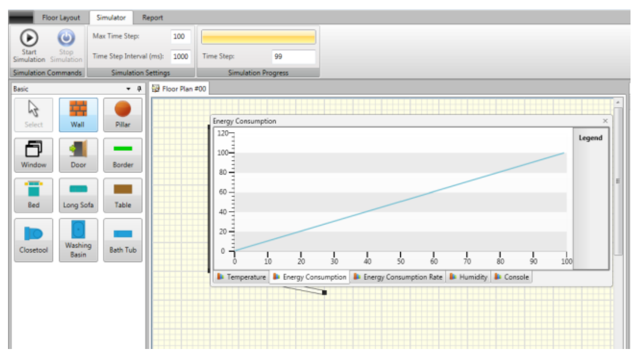


Figure 7. Power consumption before optimization

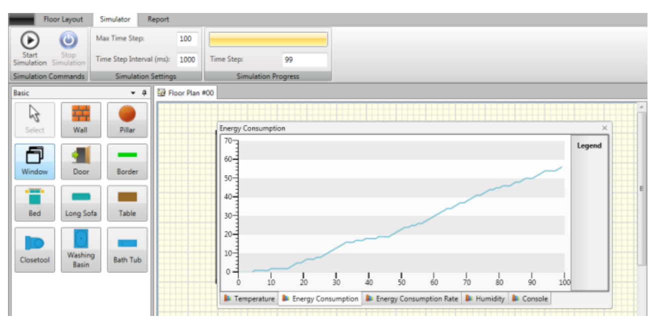


Figure 8. Power consumption after optimization by the proposed method

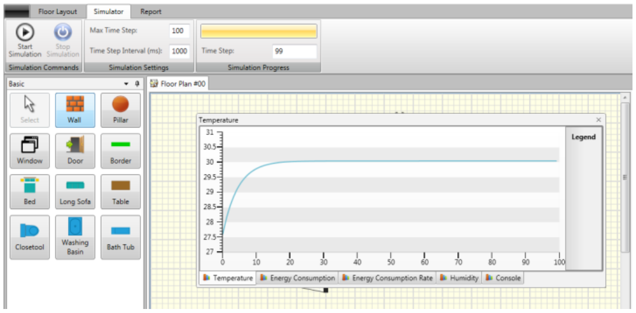


Figure 9. Temperature measurement before optimization

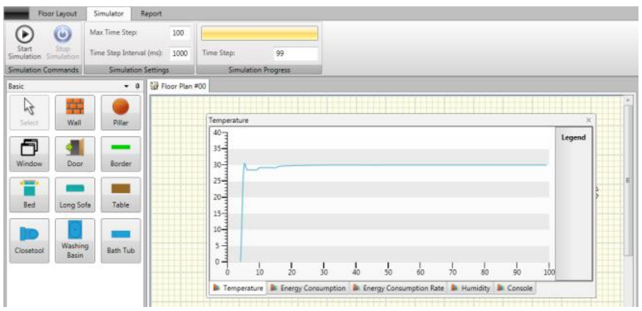


Figure 10. Temperature measurement after optimization by the proposed method

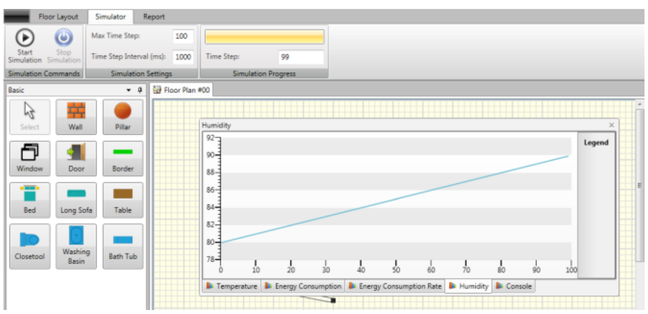


Figure 11. Humidity measurement before optimization

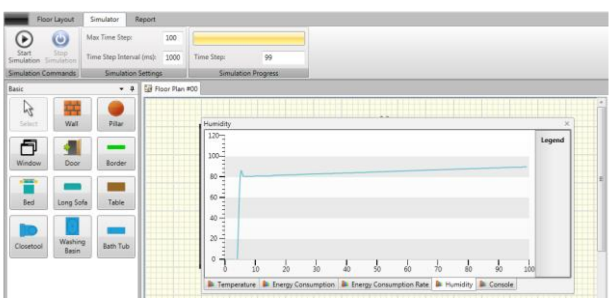


Figure 12. Humidity measurement after optimization by the proposed method

We optimize the schedule with the proposed algorithm and the generated solution is as shown in Fig. 10 and Fig. 12. User can choose the preferred schedule based on their requirement by setting the generation and population size for the optimization process. A dedicated graphical user interface has been developed bringing the benefits of the optional installation and operation of an automated system of sensors and meters, for monitoring the building energy consumption and the combination of control scenarios, so as to decrease energy consumption.

VI. Conclusion

In this paper, a new framework is presented for generating smart energy solutions to sustain a high level of occupant comfort while achieving significant energy savings. The proposed framework provides multifaceted approach with energy-efficient automation functions that makes buildings more intelligent and comfortable for occupants. The proposed algorithm is applied to optimize the requirements of the occupants' comfort and power consumption effectively. The results obtained show that the proposed approach is a viable alternative for intelligent building energy control and useful for achieving maximal occupant comfort in a building environment with higher energy efficiency.

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Yvonne Soh is a Professional Engineer and currently working as an Executive Director at Singapore Green Building Council. She graduated with a Bachelor of Engineering (Civil) from NTU and obtained her Master of Science (Civil Engineering) degree from NUS. She gained her industry experience as a civil engineer at P&T Consultants, an international multi-disciplinary building and construction consultancy firm, before joining Building Construction Authority.

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