Energy 121 (2017) 606–615

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Development of a new methodology to optimize building life cycle cost, environmental impacts, and occupant satisfaction

Ehsan Mostavi [a], Somayeh Asadi [b, *], Djamel Boussaa [c]

[a] Department of Architectural Engineering, Pennsylvania State University, 104 Engineering, Unit A, University Park, PA, 16802, USA
[b] Department of Architectural Engineering, Pennsylvania State University, 104 Engineering, Unit A, University Park, PA 16802, USA
[c] Department of Architecture and Urban Planning, Qatar University, P.O. Box 2713, Doha, Qatar

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form
18 November 2016
Accepted 9 January 2017
Available online 16 January 2017

Keywords:
Occupant satisfaction
Utility-theory
Multi-objective optimization
Building energy performance
Building envelope

ABSTRACT

Thermal comfort and occupant thermal satisfaction are critical aspects in the indoor environment quality assessment and have received considerable attention by designers and building occupants. Improper indoor temperature not only decreases the level of occupant thermal satisfaction, but also has serious health related consequences. Despite the importance of occupant thermal satisfaction that has been vastly emphasized, studies incorporating occupants' satisfaction during the design process are very limited. Therefore, this study aims to develop a multi-objective design optimization model to minimize life cycle cost and life cycle emission, and maximize occupant satisfaction level in a typical commercial building. To solve the multi-objective optimization problem, a Harmony Search based algorithm is developed and employed. Moreover, to identify the level of design thermal satisfaction, a novel utility-theory based thermal comfort index is defined and calculated. A small office building is selected as a case study to analyze four different designs which are identified as optimum solutions. To determine the optimum designs, the satisfaction level of all the design combinations having cost and emissions similar to previously distinguished optimum solutions are compared and best designs are identified.

1. Introduction

Thermal comfort and occupant thermal satisfaction are considered as critical aspects in the assessment of indoor environment quality and have received considerable attention by designers and building occupants. Thermal comfort is defined as the order at which occupants are having no intention to modify their environment [1]. Improper indoor temperature not only decreases the level of occupant thermal satisfaction, but also has serious health related consequences [1,2,3]. It is also seen that thermal comfort and in particular temperature set, have a significant impact on building energy consumption level [4]. Desire to understand the extensive influence of occupants on building energy performance has initiated large number of studies to focus on them as an important determinative subject [5,6].

Several studies have been conducted to investigate the relationship between occupants' working environment perception and their efficiency [7,8]. Moreover, studies were conducted to identify the relationship between satisfaction and different parameters including temperature, humidity, air velocity, and radiant temperature [4,9]. In a study performed by Varjo et al. [10] on satisfaction and performance of office occupants, a high decrement in working efficiency was observed among people who were working in offices with low thermal comfort.

As mentioned, various factors contribute to thermal comfort and satisfaction. Among these factors, temperature play a critical role in occupants' perception [8]. In a study performed by Huizenga et al. [7], it was seen that having personal control on indoor environmental conditions significantly increases the level of occupant satisfaction. Other study conducted by Hancock et al. [11], showed that people who are exposed to low indoor environmental quality may have different symptoms including short term memory and performance reduction due to the improper working condition. In a study performed by Li et al. [12], a multi-objective optimization model aiming to minimize the costs and maximize the thermal comfort was developed. They showed that the costs and savings are highly dependent on the occupants' requirements.

In addition, in recent decades, environmental problems, especially greenhouse gas (GHG) emissions and global warming, have enforced designers to estimate the level of environmental emission

* Corresponding author.
E-mail address: asadi@engr.psu.edu (S. Asadi).

http://dx.doi.org/10.1016/j.energy.2017.01.049
0360-5442/

of their design and reduce their environmental contribution [13,14,15]. Moreover, customer expectations regarding the project budget imposes higher pressure on designers and decision makers to reduce the project costs. To have a better understanding about environmental impacts of different projects, Life Cycle Assessment (LCA) has been extensively implemented during the last decades [16,17]. LCA includes accumulating of all environmentally relevant streams inventory associated with production processes, transportation, and demolition of a product [18]. Accordingly, a significant body of studies have been conducted to identify the optimum designs with minimum Life Cycle Emission (LCE) and Life Cycle Cost (LCC) [19]. Studies have implemented multiple strategies to provide designers with information regarding the level of environmental impacts of their design. In an innovative approach, Basbagill et al. [20] presented a methodology to provide designers with LCA data of different designs in Building Information Model (BIM). This method integrates BIM with an energy simulation model to identify the LCE of each design during the operation stage of the building lifetime. Emissions associated with other stages of design (pre-operation and maintenance/replacement) were calculated according to different databases such as SimaPro and CostLab. Although, the developed framework was well suited, lack of a unique systematic information exchange process was a barrier to expand the application of such methods [21].

However, during the design process, we should consider multiple, and usually competitive, objectives such as reduction of energy consumption, financial costs and environmental impacts. This makes the design as a challenging multi-objective optimization problem. In a very rough classification, the optimum search methods can be categorized into two classes: exact algorithms and heuristic search. The exact algorithms identify a concrete answer for the optimization problem. However, the heuristic search algorithms do not guarantee to find the best answer and there is always a probability to miss the local optimums, but they provide results with reasonable accuracy [22]. The heuristic search algorithms are problem dependent and should be adjusted for different problems. In a more advanced form, the metaheuristic search algorithms are highly problem-independent and can be applied to various types of optimization problems. Metaheuristic algorithms provide set of strategies to develop heuristic optimization [23].

Several studies have employed different metaheuristic algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Harmony Search (HS) to solve their multi-objective optimization problems [24–27]. Rapone and Saro [28] employed a PSO based algorithm to solve a single-objective optimization problem of identifying the best façade for a highly glazed building. They identified the optimum percentage and type of glazing and depth shadings to minimize the level of carbon emissions of an office building. In a study performed by Asadi et al. [29], a multi-objective optimization model using GA and artificial neural network was employed to determine the best retrofit strategies quantitatively. The proposed model determines the tradeoff between retrofit cost, energy consumption, and hours of occupant discomfort. Building envelope and selection of proper materials for building façade have always received significant attention [30]. Fesanghari et al. [31] employed a HS based optimization algorithm to determine the best combination of building envelope to minimize the LCC and LCE of the project. In another study conducted by Ascione et al. [32], a GA method was employed to determine the best mix of renewable energy for a residential building. The objective of this study was to minimize the primary energy demand and investment cost. In addition to selecting the best materials, some studies have focused on identifying the optimum window to wall ratio and windows geometry [33]. In another study, Ruiz et al. [34] utilized a Tabu Search algorithm to identify the proper materials and HVAC system with lower investment cost and energy demand for residential buildings. Tabu search has similar behaviors as GA, however it has better performance in local searches, while GA has a better global performance.

As it was explained so far, multiple heuristic algorithms have been successfully employed in different optimization problems. Each of these algorithms uses different strategies to solve specific range of problems, but not all of them. For example, PSO generates a semi-random movement of population of birds (particles) to identify the location of the optimum solution through the search environment; while, GA utilizes the genetic recombination of random generated parents to attain new generations. Different characteristics of HS algorithm, such as using single-point random search with an improving memory, has empowered the method to identify the local optimums with better precision and fewer mathematical requirements. Moreover, comparing the exploration and focusing ability of mentioned algorithms, HS algorithms shows better operation.

Targeting to involve the end user satisfaction into design process, the objective of the current study is to identify the optimum designs having lowest LCC and LCE as well as highest thermal satisfaction. To attain this objective, the effect of different construction materials in various building components including external and internal wall system, glazing system, floors, roof and ceiling on the LCC, LCE and occupant satisfaction were investigated. To solve the multi-objective optimization problem, a HS based algorithm is developed and employed.

2. Methodology

2.1. Design variables

To investigate the effect of different building construction materials on defined objective functions, a database including 65 different materials was inserted to the optimization code. Table 1 shows variables included in the database. Different building components including walls, floors, ceilings, glazing system, doors were considered in this study. This database includes physical and thermal properties of materials as well as associated environmental emissions to calculate LCE and LCC. Table 2 shows number of layers and the range of variables considered for each element. For instance, living room external walls are considered to have 4 different layers and the materials that can be assigned to the 4th layer are 19, 20, and 21 which are gypsum boards with different thicknesses.

2.2. Objective functions

Current study proposes a multi-objective optimization process to minimize the LCC and LCE as well as maximize the occupants' thermal comfort (TC). Since several variables affect building energy performance [35], the process of identifying the optimum design is time consuming. Therefore, it is necessary to use a heuristic algorithm to accelerate the process of identifying a proper approximate result. The general procedure of heuristic optimization algorithms are similar, however, the main search engines and their ability in identifying the local optimums are different [36].

Fig. 1 shows a schematic view of the developed optimization code. As it can be seen in this figure, the process of optimization includes three steps: simulation, evaluation, and improvement [37,38]. The simulation step includes running the energy simulation software and determining the magnitudes of energy consumption, zone temperatures, and environmental emissions. EnergyPlus V8.4 [39] which is a powerful and reliable energy simulation software, and has the highest utilization share between the energy