Study of Factors Influencing Room Ambient Temperature Using Design of Experiments

Malek Almobarek & Kepa Mendibil
Department of Design, Manufacturing & Engineering Management
University of Strathclyde
Glasgow, UK
malek.almobarek@strat.ac.uk, kepa.mendibil@strath.ac.uk

Abdallah Alrshdan
Industrial Engineering Department
Alfaisal University
Riyadh, Saudi Arabia
aalrshdan@alfaisal.edu

Abstract

The thermal comfort inside the rooms at commercial buildings is concerning the responsible people of operating these rooms as they may receive regular complaints from the occupants requesting more cooling. So, this paper presents a framework to set the ambient temperature for optimal thermal comfort in commercial buildings. Two operational parameters of the cooling systems were proposed to control the ambient temperature. The parameters are airflow and valve opening which are usually variables determined at the design stage of the cooling system. The design of experiment analysis is utilized to find the optimal setting of these parameters. Only two levels of each parameter were investigated (Low, High). A 2^2 complete randomized factorial design is proposed for the analysis. The framework was implemented at Alfaisal University classrooms. It was found that the optimal thermal comfort can be achieved by setting the parameters at their lower levels.

Keywords
Ambient Temperature; Cooling; Design of Experiments; Factorial Design; Commercial Buildings.

1. Introduction

Ambient temperature (AT) is the air temperature of a space or an area where someone or something is utilized, and its adjective is related to the immediate surroundings. Also sometimes referred to as an ordinary temperature or a baseline temperature and it is important for system design and thermal analysis (Rouse, 2019). AT plays important role in different applications. For instance, it is important to growth and induction of flowering (McClung *et al*, 2016). AT can be considered as part of thermal comfort, which is providing comfortable temperature to the occupants. Recently, three adaptive thermal comfort standards are comprehensively reviewed and compared through a case study from Netherlands as adaptive model is mainly based on the theory of the human body's adapting to its outdoor and indoor climate (Taleghani, 2013).

Here in this research, AT in commercial buildings (CB) are addressed, which is maintained and controlled by the related units such as air handling unit and fan coil unit (FCU) (Arthur & Larson, 2016). There are several research applications about AT, a well comprehensive evaluation of the effectiveness of Phase Change Materials (PCMs) to improve the thermal comfort in lightweight buildings during summer using simulations (Evola, 2012). Another study obtained on human metabolic rate of building occupants, but it is probably not accurate enough to sustain common thermal comfort modelling with any semblance of precision (Luo *et al*, 2018). As thermal comfort is concerned, a literature review was critically preformed in buildings using radiant as well as all-air systems and accordingly, there is suggestive evidence that radiant systems may provide equal or better comfort than all-air systems (Karmann *et al*, 2016).

Going through the related research, it has been found that a lot of experiments were conducted about AT and its related subject. It is considered as a factor affecting physiological response of broiler chickens (Donkoh, 1989). In

Malaysia, a few experiments were conducted to investigate the effect of single variables, such as AT, thermostat setting positions and door opening, and their combined effect on energy consumption (Saidur *et al*, 2001). There are experiments were carried out to determine the effect of an underfloor air-conditioning system on comfort (Lian & Wang, 2011). The experiments had evaluated four factors, which were the type of outlet, the distance between the outlet and the occupant, the velocity of the supply air, and the temperature of supply air. It was found that the distance between occupant and outlet has a significant influence on thermal comfort, the velocity and temperature of the supply air have a moderate influence, and the type of outlet has little influence. Recommended values of these factors were developed that would achieve thermal comfort and the related results provide reference data on air distribution in underfloor air-conditioned rooms. Therefore, airflow is one of the top factors that affecting the comfort inside the rooms (Richardson, 2017).

In this research paper, design of experiments (DoE) is utilized to study the immediate mechanical factors that are affecting AT and to determine the levels of factors that will provide the maximum cooling comfort. The factors under study are airflow and cooling valve opening at any room inside a CB.

2. Methodology

DoE is an advanced statistical tool to study efficiently the effect of many variables with a minimum effort in data collection. In this research, the effect of airflow and chilled water/cooling valve opening of the FCU, which has no direct control by the user/ operator, on the AT of a room is studied. It is to be noted, FCU is an air-conditioning unit which controls the AT of a typical room using fan speed and chilled water (Oasis-aircon, 2020). The exact method used in this research is the 2^2 Design. It is the simplest type of 2^k design, which is one of the arrangements of the basic experimental factorial design for process improvement (Montgomery, 2012). The target of this study is to investigate the effect of operational factors of cooling system on AT and check which levels combination provides the maximum cooling outputs.

In this paper, administrative outlines, which are listed below, are recommended for the users, operators, or the managers to go through them; to achieve the study target.

1) Identifying the room(s), which is/ are experiencing issues with AT's cooling comfort.
2) Formulating the factors with their levels as per Table 1, which is proposed to provide the needed design framework to carry out the factorial experiment.

Table 1: Response – AT (°C)

Factors	B	
A	B_1	B_2
A_1	X_1	X_2
A_2	X_3	X_4

Where:
A: First factor: Airflow - Unit: CFM (Cubic Feet per Minute).
B: Second Factor: Chilled Water/ Cooling Valve Opening - Unit: %.
A_1: Lower level of first factor. Practically, it is called "Low", but the user is recommended to go through the mechanical manuals to check the exact nomination, if any. These manuals should be available in the documents received at the time of handing over the building to the ownership of his/ her organization.
A_2: Upper level of first factor. Practically, it is called "High", but the user is recommended to do the same as A_1.
B_1: Lower level of second factor. To identify that, the user should check the mechanical manuals, which are clarified above.
B_2: Upper level of second factor. To identify that, the user should do the same activity of A_1 or B_1.
X_1: Data/ Reading of AT under the setup of both A_1 and B_1.
X_2: Data/ Reading of AT under the setup of both A_1 and B_2.
X_3: Data/ Reading of AT under the setup of both A_2 and B_1.
X_4: Data/ Reading of AT under the setup of both A_2 and B_2.

The said data can be collected through building management system (BMS) and can be done at different time periods (Blokdyk, 2020). It is recommended to do the sampling during the occupancy hours and can be averaged on certain days as needed.

3) Using Minitab 19 or any other resources to implement the experiment by following the steps that are outlined in the next application section.

5. Application and Results

In this paper, Alfaisal University, Riyadh, KSA, is used as a case study. One of the classrooms (BG.68) was chosen to be observed and to implement the experiment.

5.1. Factors and Levels Nominations

- Factor A: Airflow (CPM)
- Factor B: Cooling Valve Opening (%)
- Level A_1: Low
- Level A_2: High
- Level B_1: 25 %
- Level B_2: 75 %

5.2. Data Collection

Data have been taken every 1 hour on each working day (Excluding Fridays and Saturdays) over a period of one month (October 2020) at different airflow and valve settings. The readings then were averaged per day basis i.e., average temperatures on Sundays, Mondays, etc. Table 2 furnishes the data in this regard.

5.3. Data Entry

Minitab 19 is used to run this experiment (Minitab.com, 2020). The data mentioned in previous table have entered as shown in Table 3.

5.4. Results

After running the experiment, Table 4 shows the computed results of the ANOVA test. With (significance level $\alpha = 0.05$) both flowrate and valve opening have a significant effect on thermal comfort. Moreover, a very low probability value (P-value) confirmed the model is statistically significant. The coded regression model for thermal comfort (T_χ) shown in equation 1 was found to have R^2 and adjusted R^2 of 94.74% and 93.75% respectively demonstrating a high goodness of fit. The normality and equality of variance assumptions of the two variables were assessed and verified using residual plots (Figure 1).

$$T_\chi = 21.8410 - 0.3810\ A - 0.5090\ B + 0.0130\ A*B \qquad (1)$$

Table 2: Response of BG.68 – AT (ºC)

Factors	B: CHW/ Cooling Valve Opening (%)									
A: Airflow (CFM)	Low					High				
	Sun	Mon	Tue	Wed	Thu	Sun	Mon	Tue	Wed	Thu
Low	22.4	22.52	23.04	22.9	22.86	21.51	21.72	21.63	21.88	21.76
High	21.81	21.92	22	22.07	21.98	21.02	20.93	20.87	21.11	20.89

Table 3: Data Entry (Snapshot)

Worksheet 1 ***

↓	C1	C2	C3	C4	C5	C6	C7
	StdOrder	RunOrder	CenterPt	Blocks	Factor A: Air Flow (CFM)	Factor B: Cooling Valve Opening	Temp. (oC)
1	1	1	1	1	-1	-1	22.40
2	2	2	1	1	1	-1	21.81
3	3	3	1	1	-1	1	21.51
4	4	4	1	1	1	1	21.02
5	5	5	1	1	-1	-1	22.52
6	6	6	1	1	1	-1	21.92
7	7	7	1	1	-1	1	21.72
8	8	8	1	1	1	1	20.93
9	9	9	1	1	-1	-1	23.04
10	10	10	1	1	1	-1	22.00
11	11	11	1	1	-1	1	21.63
12	12	12	1	1	1	1	20.87
13	13	13	1	1	-1	-1	22.90
14	14	14	1	1	1	-1	22.07
15	15	15	1	1	-1	1	21.88
16	16	16	1	1	1	1	21.11
17	17	17	1	1	-1	-1	22.86
18	18	18	1	1	1	-1	21.98
19	19	19	1	1	-1	1	21.76
20	20	20	1	1	1	1	20.89
21	21	21	1	1	-1	-1	22.40
22	22	22	1	1	1	-1	21.81
23	23	23	1	1	-1	1	21.51
24	24	24	1	1	1	1	21.02
25	25	25	1	1	-1	-1	22.52
26	26	26	1	1	1	-1	21.92
27	27	27	1	1	-1	1	21.72
28	28	28	1	1	1	1	20.93
29	29	29	1	1	-1	-1	23.04
30	30	30	1	1	1	-1	22.00
31	31	31	1	1	-1	1	21.63
32	32	32	1	1	1	1	20.87
33	33	33	1	1	-1	-1	22.90
34	34	34	1	1	1	-1	22.07
35	35	35	1	1	-1	1	21.88
36	36	36	1	1	1	1	21.11
37	37	37	1	1	-1	-1	22.86

Current Worksheet: Worksheet 1

According to the full model, the interaction is found to be insignificant. Table 5 shows the ANOVA results of the reduced model without the interaction effect. The lack of fit is found to be insignificant supporting the model adequacy. The maximum predicted thermal comfort is 22.75 as shown in the surface plot Figure 2. According to the contour plot of the model, the maximum thermal comfort can be achieved by moving toward the low levels of both air flow and valve opening as shown in Figure 2.

Table 4: Computed Results for BG.68

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	8.08822	2.69607	96.00	0.000
Linear	2	8.08484	4.04242	143.94	0.000
A (Valve opening)	1	2.90322	2.90322	103.37	0.000
B (Air Flow)	1	5.18162	5.18162	184.50	0.000
2-Way Interactions	1	0.00338	0.00338	0.12	0.733
A*B	1	0.00338	0.00338	0.12	0.733
Error	16	0.44936	0.02808		
Total	19	8.53758			

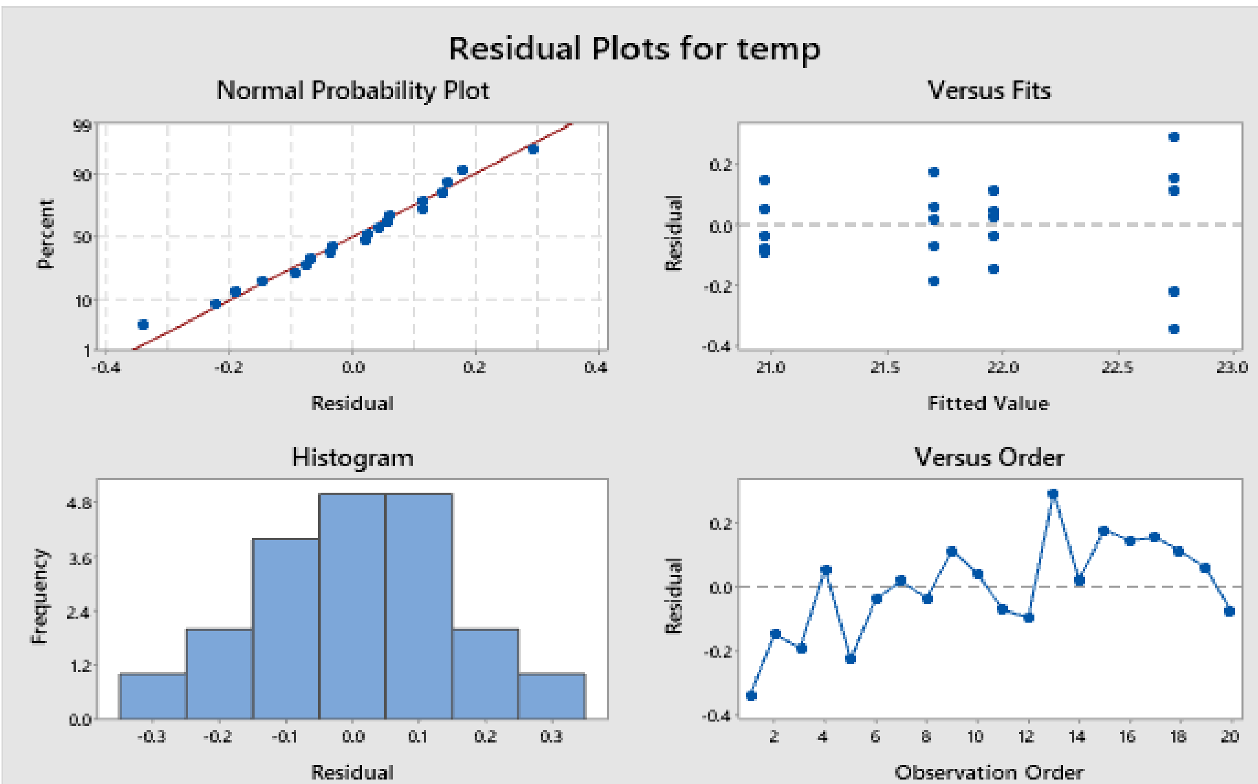

Figure 1: Residual Plots for of the predicted model of BG.68

Table 5: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	2	8.08484	4.04242	151.79	0.000
Linear	2	8.08484	4.04242	151.79	0.000
A	1	2.90322	2.90322	109.01	0.000
B	1	5.18162	5.18162	194.57	0.000
Error	17	0.45274	0.02663		
Lack-of-Fit	1	0.00338	0.00338	0.12	0.733
Pure Error	16	0.44936	0.02808		
Total	19	8.53758			

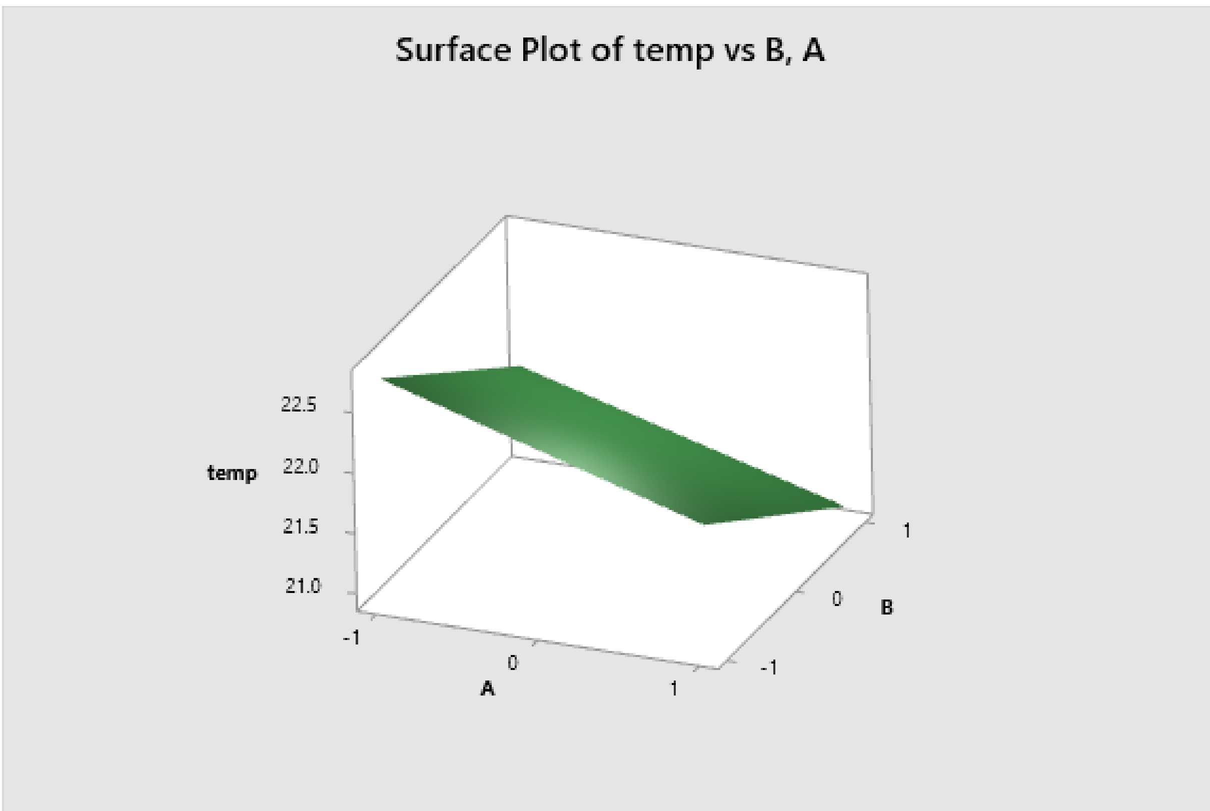

Figure 2: Surface plot of the predicted model

6. Conclusion

Factorial design has given a valid outcome to this study. The results delivered a significant managerial impact to the operators for their daily operational works. It opened a window to control one part of heat, ventilation, and air-conditioning (HVAC) system's various parts as the outcome leads the operators to identify the factors effecting AT in a typical room located at a standard commercial building as well as to determine the levels of that factors. The proposed framework can be used to investigate more factors and levels employing higher-order factorial designs.

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Biography

Malek Almobarek is a Saudi national. He was born on April 1983 in Kuwait City. He took his primary and secondary education at AlMawardi School where he was a consistent honor student. He graduated in Industrial Engineering from King Saud University in the year 2009. He did assistance to his professors at the same university with tutorial & site visits for the students before starting his experience journey by taking up a job as Plants Equipment Specialist in O&M department at GASCO, Riyadh. He worked there from May 2009 to Sep 2011. He then moved to Dallah Hospital, Dallah Health Co., Riyadh to work as Engineering Department Manager from Sep 2011 to Nov 2013. Thereafter, He joined Alfaisal University as Facility manager in Dec 2013 and currently discharging his duties as Senior Facility Manager. The areas of responsibility in his current job include Buildings and grounds maintenance; Projects; Cleaning; Catering and Leasing; Health and Safety; Procurement and Contract management; Security; Space management; Waste disposal; Mails, Housing and Transportation; Utilities and Campus infrastructure. It is here that he decided to further his studies while continuing to work and joined in Master of Engineering Management (MEM) program that Alfaisal University was offering. He scored GPA 4.0/4.0 and completed a research thesis on Water Budget Control Framework Using DMAIC Approach for Commercial Buildings. He graduated in April 2020 with a first honor and now is a full time PhD student in Design, Manufacturing and Engineering Management at University of Strathclyde, UK. Eng. Malek is a result oriented, Innovative, resilient, and collaborative. He is not only very good in academics, but also, he is an expert in Facility and Project Management; Procurement and Inventory Management; Supply Chain Management; Emergency Response; Environmental Control; Security Control; Contractor Oversight; Resource Allocation; Building Regulations; Building Systems; Fire Safety; Scheduling; Processes and Procedures; Hazardous Waste, etc. He is a member of Saudi Council of Engineering in the capacity of Professional Engineer and loves travelling, reading, bowling, and watching debates on TV.

Abdallah Alrshdan is an assistant professor in Industrial Engineering at Alfaisal University, Saudi Arabia. He teaches courses in Ergonomics, Work Design, Data analytics, and Quality Engineering. His PhD in Industrial Engineering is from Wichita State University. His current research focuses on ergonomics product design, applications of AI in the design and manufacturing process, and lean production. He worked as a production manager at ALL Cell technologies in USA building Li-ion batteries used for electrical cars and continues as a consultant in the research and development department. Dr. Alrshdan is currently the chair of the Industrial Engineering department and the head of quality assurance. He serves as a reviewer for different international journals and session chair in international Industrial Engineering conferences.