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Tuning approach of dynamic control strategy of temperature set-point for existing commercial buildings

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Abstract. Indoor environmental parameters especially the air temperature have substantial effect on energy consumption in commercial buildings and indoor thermal comfort. This study presents a tuning approach of dynamic control strategy of temperature set-point with a view to improving occupants' thermal comfort while simultaneously minimizing energy consumption. To determine optimum temperature set-points in response to ambient conditions, this study investigates the thermal comfort conditions of a commercial building based on real time series data. To quantify thermal environmental conditions for human occupancy, this study uses the graphical comfort zone method proposed by ASHRAE Standard 55-2017 through a rigorous analysis. Based on this analysis the study narrows down the comfort range in the context of seasonal variations and proposes tuning the Master Temperature Set-Points (MTSP) with 4.8^oC variable linear band between upper and lower temperatures dependent on a simple algorithm. This re-setting strategy of temperature set-point ultimately offers extended lower and upper boundary limit for variable linear band. Extension of linear band for MTSP reduces the gap between temperature set-point and outdoor temperature which ultimately offers less heating and cooling energy consumption. Results show that implementation of this proposed approach would lead to monthly 2707.94 kWh energy savings either from heating or cooling or both during winter and summer season.

Keywords. Tuning approach; Temperature set-point; Energy consumption; Thermal comfort.

1. Introduction

Building sectors account for about 33% of the total primary energy resources around the world [2, 3] and 30% of worldwide CO₂ concentrations [3]. Energy used by the building sector is rising over the years due to the wider application of HVAC systems in response to the growing demand for better thermal comfort within the built environment. Therefore, improvement in HVAC energy efficiency is necessary from the perspective of energy savings. Energy consumed by the HVAC system is considerably influenced by the seasonal variations and daily weather conditions. In this regard, building indoor temperature set-point which can be adjusted according to outdoor temperature, plays an important role. An optimal adjustment of temperature set-point can reduce the heating or cooling energy consumption by narrowing down the difference between building indoor and outdoor temperatures. In addition, it is important to maintain an optimum dynamic temperature set-point in response to ambient conditions to ensure satisfactory indoor thermal conditions for the building occupants.

While a good number of studies concentrated on optimal adjustment of heating or cooling temperature set-point, in a majority of studies energy savings have been prioritized over occupant thermal comfort. Aghniaey and Lawrence [4] reported that the literature concerning the impact of increased cooling set-point temperature on occupant thermal comfort during demand response (DR) events are mostly on the energy saving potential. Luzi, et al. [5] proposed a tuning methodology of model predictive control design aiming at identifying the best parameter set in terms of energy savings



and temperature deviation from the chosen set-point. According to their simulation based analysis, the proposed approach can save from 0.9% to 5.2% energy consumption. Roussac, et al. [6] reported that by rising 1°C in the summer set-point temperature (SST) and dropping 1°C in the winter set-point temperature (WST), around 6% electricity consumption can be reduced from the HVAC system in Australian office buildings.

Further, some studies e.g. [7, 8] concentrated on adaptive models with wider ranges of comfort zones with a view to reducing energy consumption. To achieve the acceptability of these adaptive models, wide-ranging techniques/strategies i.e. general adaptability, operable windows, elevated air movement, personal controls etc. have been implemented. However, implementing these strategies incurs capital investment which has hardly been addressed by past studies. Hoyt, et al. [7] suggested extending air temperature set-point based on simulated results of energy savings. Even though that study used ASHRAE Standard 55 [1] as the reference adaptive model, the study lacks the analysis of occupants' conditions. Also, Ghahramani, et al. [8] recommended widening the variable linear band for indoor temperature set-point to reduce the heating energy consumption in their studies. However, this study was based on a simulated building model which does not represent actual occupancy profiles and load conditions. Furthermore, the simulated models were exempt from time related and comfort related constraints.

Therefore, it is necessary to concentrate on real buildings to study the techniques of learning optimal set-points. Studying optimal temperature set-points in a real building can offset the problem of assuming uniform control parameters for all zones within a building. Also, while performing optimal adjustment of temperature set-point, it is important to balance between occupant thermal comfort and energy savings. To ensure occupants' thermal comfort, it is crucial to follow a systematic procedure to quantify thermal environmental conditions for the occupants in the context of seasonal variations.

In view of this context, this study concentrates on investigating the indoor thermal comfort conditions of a real commercial building for the purpose of improving occupants' thermal comfort level while simultaneously optimizing heating and cooling energy consumption.

2. Case Study

As specified in an earlier study [9] of the authors, a library building where the occupancy pattern is not predefined has been chosen for this study and also, there is no fixed occupied hour for the occupants. Due to occupants' dissimilar time schedule, the entrance and exit gates remain open frequently causing considerable heat loss or heat gain within the indoor environment during the winter or summer period. This heat effect may not be uniform throughout the building. Hence, it is essential to survey the indoor environment for different zones.

The selected building is a multi-storey 5873 m² Gross Floor Area, 3853 m² Useable Floor Area building comprising four levels. The latitude and longitude of this building are 32.0675°S and 115.8351°E respectively and is located in a semi-arid region. During the occupied hours, occupancy level varies considerably in Level 2 and 3. Level 4 featuring office activities maintains almost fixed occupancy level throughout the day. Detailed information about this building configuration, opening hour in each level and operating strategies of associated HVAC systems were presented in an earlier study [9] of the authors.

As indicated in an earlier study [9] of the authors, level 2 is affected by heat loss or heat gain more than any other levels as this level maintains a 24/7 opening hour. Because of this variable occupancy pattern throughout the day, this study only concentrates on Level 2 of the study building for data analysis. This Level is bounded on three sides by basement walls with the remaining facade being approximately 50% cavity wall and 50% metal framed glazing [10]. This level is equipped with twenty-one variable air volume (VAV) boxes – 12 VAV boxes are controlled by west side air handling unit (AHU) and the rest 9 VAV boxes are controlled by east side AHU. The present study reflects the indoor thermal conditions of 12 zones corresponding to 12 individual VAV boxes controlled by the west side AHU.

3. Methodology

This study concentrates on quantifying potential energy savings by performing optimal adjustment of temperature set-point. To determine optimum temperature set-points in response to ambient conditions, this study investigates the thermal comfort conditions of a real commercial building based on real time series data retrieved from the Murdoch University Building Management System (BMS) [11] and

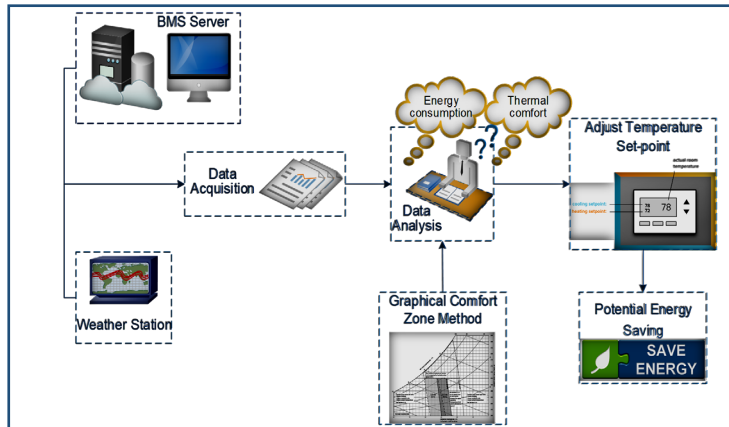


Figure 1. A step by step methodological approach

Weather Station [12]. The existing strategy of adjusting the temperature set-points within the prescribed linear band and its relation with ambient conditions is studied to suggest possible tuning potential in the context of energy saving and improved thermal comfort conditions for the occupants. To quantify thermal environmental conditions for human occupancy, this study uses the graphical comfort zone method proposed by ASHRAE Standard 55-2017 through a rigorous analysis. Based on this analysis this study narrows down the comfort range providing optimized heating energy consumption and improving occupants' thermal comfort level. A step by step methodological approach is portrayed in Figure 1.

4. Results and Discussion

To inspect the study building's indoor environmental conditions for individual zone, two individual months' (June 2017 and February 2019) indoor and outdoor corresponding data are analysed. The month of June represents winter season and coldest time of the year as per Nyoongar seasonal calendar of Australia while February represents summer season and hottest month of the year of Australia [13]. In an earlier study of the authors [10], the study building's indoor environmental conditions for individual zone are analysed for winter season. To validate that analysis results this study conducts the survey for summer season. Afterwards a comparative analysis has been performed in terms of energy savings. As an example, this study presents one-day data (9:00 AM 7 Feb. – 9:00 AM 8 Feb. 2019) analysis result for summer season.

As specified in an earlier study of the authors [10], the stated University BMS maintains a Master Temperature Set-Point (MTSP) with 2°C variable linear band between upper and lower temperatures based on a simple algorithm. This MTSP is selectively used to vary the set point of certain spaces in relation to the outside air temperature (OA-T). The following algorithm is used to control the MTSP. For $OA-T \leq 18^{\circ}C$ MTSP = 22.5°C; For $OA-T \geq 32^{\circ}C$ MTSP = 24.5°C

For $18^{\circ}C < OA-T < 32^{\circ}C$, MTSP linearly scales between 22.5 - 24.5°C. Therefore, 22.5°C and 24.5°C imply respectively winter set-point temperature (WST) and summer set-point temperature (SST). When $OA-T \leq 18^{\circ}C$ the authors proposed lowering the WST to 21.9°C in the earlier study [10].

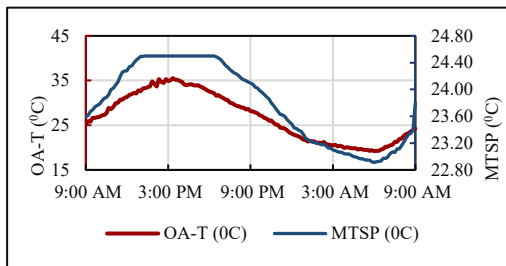


Figure 2. Fluctuations in MTSP with OA-T

Figure 2 shows that the MTSP is varying all over the day (9:00 AM 7 Feb. – 9:00 AM 8 Feb. 2019) depending on the dynamic value of OA-T. Note that between 12:30pm to 6:20pm OA-T exceeded 32°C which resulted in constant MTSP during that period.

Figure 3 compares the ranges of indoor temperatures for individual zones and associated common MTSP for all zones over 24 hr period. The ranges are determined for individual zones based on fluctuations of indoor temperature and MTSP throughout the day. This Figure clearly depicts that the fluctuating patterns of indoor

temperatures are different for individual zones despite a common MTSP is maintained within all zones. This can happen due to outside weather variations, occupancy level and thermal coupling with the adjacent spaces. To receive profound perception about indoor thermal conditions of these twelve zones on the specified day, the presented (Figure 3) ranges of indoor temperatures are compared against ASHRAE Standard 55-2017. According to ASHRAE Standard 55-2017 indoor temperature should be within 67.3-82.76 °F (approx. 19.60 -28.2°C) to satisfy thermal environmental conditions for human occupancy [1]. This Figure illustrates that all ranges of indoor temperatures fall within the bounded area of comfort zone.

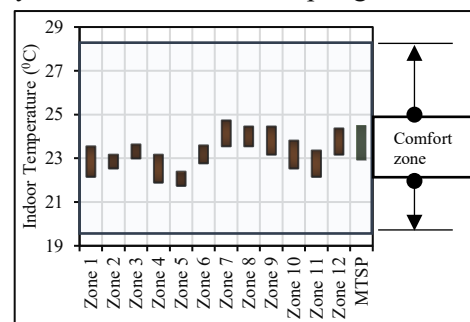


Figure 3. Ranges of indoor temperatures and MTSP for individual zones fluctuated over 24

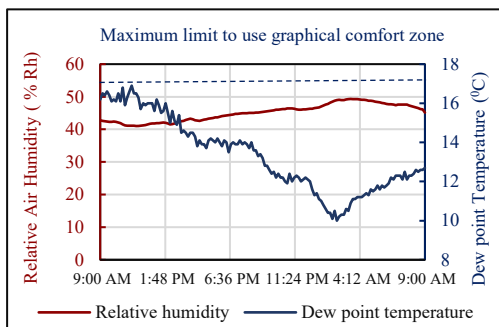


Figure 4. Changes in air relative humidity and dew point temperature

Similar to an earlier study of the authors [10] this study also considers indoor relative humidity to narrow down the comfort range with a view to improving the satisfactory level of thermal comfort and optimizing HVAC energy consumption. The changes in relative humidity on the specified day are presented in Figure 4. This Figure demonstrates that during that one-day period relative humidity changed by around ±5% from 45%.

According to ASHRAE Standard 55-2017 [1] there are three methods for determining acceptable thermal environments in occupied spaces. To decide which method is applicable for this study, it is necessary to evaluate occupants' metabolic rate, clothing insulation, average air speed and humidity ratio or dew point temperature with respect to occupants' building category and seasonal changes. Based on study building's general library activities, it can be assumed that occupants' activities are limited to reading, seated; writing; typing or filing, seated for which metabolic rate is within 1.3 met. Since the studied data symbolizes summer season, therefore, it can be assumed that occupants' common clothing is a short-sleeved shirt and trousers for which clothing insulation I_{cl} is 0.5 clo. It is also assumed that on the specified day average air speed (V_a) was ≤ 0.2 m/s (40 fpm) since no elevated air speed was applied. To examine the dew point temperature, t_{dp} on the stated day, it is charted in Figure 4. This Figure shows that t_{dp} was $\leq 16.8^\circ\text{C}$ which is the first requirement of using graphical comfort zone method. Also, other requirements of graphical comfort zone method such as metabolic rates for occupants between 1.0 and 1.3 met, clothing insulation I_{cl} between 0.5 and 1.0 clo and average air speed (V_a) ≤ 0.2 m/s are satisfied to use this method in the present study.

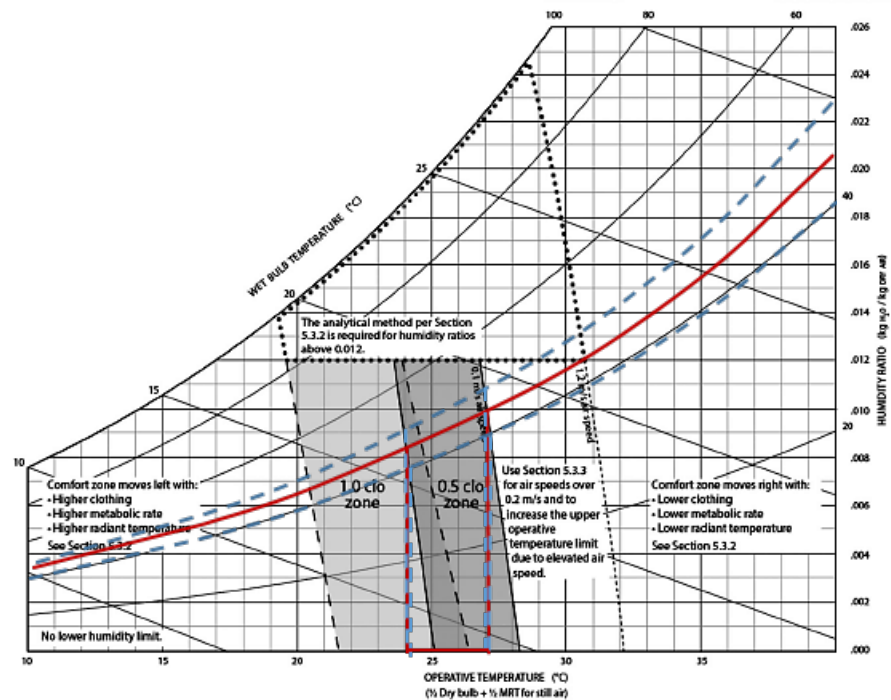


Figure 5. Graphic Comfort Zone Method: Acceptable range of operative temperature that meet the specified criteria [1]

0.5 and 1.0 clo and average air speed (V_a) ≤ 0.2 m/s are satisfied to use this method in the present study.

Figure 5 presents the acceptable range of operative temperatures as per graphical comfort zone method. In the Figure comfort zone has been portrayed as two separate bounded areas featuring Summer and Winter comfort zones of the ASHRAE Standard 55 for 0.5 (a short-sleeved shirt and trousers) and 1.0 (a winter business suit) clothing levels respectively. This study only considers summer comfort zone since the analysed data characterizes Summer season. Relative humidity has been considered 45% (Figure 5) during the specified day as there is minor changes in operative temperature due to $\pm 5\%$ changes in relative humidity. Therefore, considering 45%RH and 0.5 clo, the acceptable range of operative temperature is found to be 24-27°C which has been outlined in Figure 5.

In an earlier study of the Authors [10], it was demonstrated that for the stated thermal conditions indoor temperature is more or less equivalent to operative temperature. Therefore, it can be considered that the accepted specific range of indoor temperature for the specified thermal conditions is 24-27°C.

Figure 6 illustrates the accepted specific range of indoor temperature obtained from ASHRAE

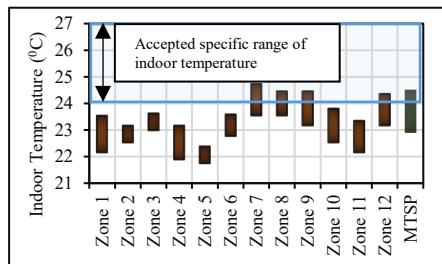


Figure 6. A bounded area showing the accepted specific range of indoor temperature

Standard 55 and compares that with the studied ranges of indoor temperature for 12 zones. As shown in this Figure, the studied ranges of indoor temperatures do not satisfy the acceptable thermal environmental conditions as per ASHRAE 55-2017. The ranges of indoor temperatures for eight studied zones are below the accepted specific range of indoor temperature. On the other hand, for rest of the four zones a certain portion of the studied ranges of indoor temperatures fall within the bounded area of specific comfort zone. Also, the observed varying MTSP do not satisfy the acceptable thermal environmental conditions. Therefore, it is necessary to optimize the variable linear band of MTSP to improve occupants' thermal comfort level.

Figure 6 indicates that the lowest limit for these studied indoor zone temperatures is approximately 2.2°C lower than the lowest boundary limit for the specific comfort zone. Therefore, from the perspective of optimal MTSP, the SST can be increased by 2.2°C which may induce the changing temperatures of studied zones to fall within the comfort zone. Raising the SST by 2.2°C implies that for $\text{OA-T} \geq 32^{\circ}\text{C}$, $\text{MTSP} = 26.7^{\circ}\text{C}$. Besides, according to Afroz, et al. [10] WST should be lowered to 21.9°C . Therefore, for $18^{\circ}\text{C} < \text{OA-T} < 32^{\circ}\text{C}$, MTSP should be linearly scaled between $21.9 - 26.7^{\circ}\text{C}$ to satisfy the thermal comfort conditions.

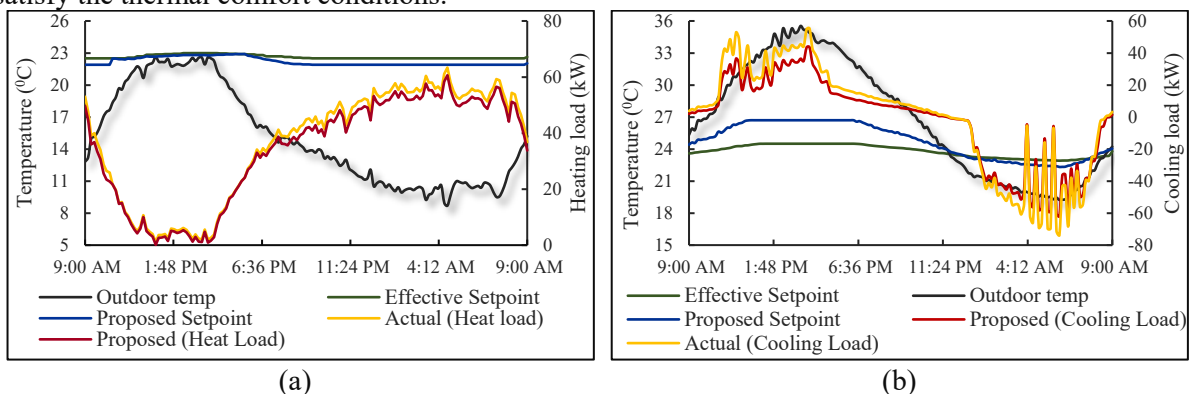


Figure 7. Comparison of actual and proposed MTSP with OA-T and associated heating/cooling load (a) 1-2 June 2017, (b) 7-8 Feb. 2019¹

Figure 7(a) and 7(b) show the changing patterns of actual and proposed temperature set-point with respect to outdoor temperature for two specified days representing winter and summer season respectively. The proposed pattern of temperature set-point lowers the gap between temperature set-point and outdoor temperature which ultimately brings down the heating or cooling load. As shown in Figure 7 selecting optimal MTSP would lead to decrease in heating and cooling load by $0.02-3.30 \text{ kW}$ and $0.07-16.40 \text{ kW}$ respectively. Therefore, on an average monthly 2707.94 kWh energy could be saved either from heating or cooling or both during winter and summer season.

5. Conclusion

Building indoor temperature set-point plays an important role in controlling the thermal comfort conditions of a space as well as to regulate energy consumption intensity. This study presents a dynamic control re-setting strategy of temperature set-point with a view to improving occupants' comfort level while simultaneously minimizing energy consumption. This study investigates the thermal comfort conditions of a commercial building based on real time series data to determine optimum changing temperature set-points in response to ambient conditions. Based on thermal comfort studies, this study narrows down the comfort range in the context of seasonal variations and proposes tuning the Master Temperature Set-Points (MTSP) with 4.8°C variable linear band between upper and lower temperatures.

¹ The negative value of cooling load indicates heating load.

This re-setting strategy of temperature set-point provides extended lower boundary limit for variable linear band. Extension of linear band for MTSP reduces the gap between temperature set-point and outdoor temperature which eventually provides less heating and cooling energy consumption. Results show that implementation of this proposed approach would lead to 0.02-3.30 kW and 0.07-16.40 kW decrease in heating and cooling load. Consequently, on an average monthly 2707.94 kWh energy could be saved either from heating or cooling or both during winter and summer season. As a future work this study will be extended to investigate if the optimum set-points as anticipated maintains zone temperatures within the thermal comfort zone.

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