Thermal Environments and Thermal Comfort Impacts of Direct Load Control Air-conditioning Strategies in University Lecture Theatres

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ABSTRACT

As a common approach to manage peak electricity demands associated with air-conditioning (AC), the Direct Load Control (DLC) strategy has yielded positive results in residential and small commercial buildings in countries that include USA, Australia and Canada. However, in educational settings with high occupant density and ventilation requirements, thermal comfort impacts of DLC remain unclear. EnergyPlus was used to simulate thermal environments inside a typical Australian university lecture theatre during DLC events under various cycling schemes, cooling set-point temperatures, building envelope thermal performance specifications and ventilation rates. The analysis explores thermal comfort impacts by applying the PMV/PPD index to simulated indoor climates. Results indicate that off cycle fraction (duration of AC compressor being off during an activation period), cycling period (time for a complete cycle) and cooling set-point temperature have relatively large influences on occupant comfort compared to the building envelope's thermal performance and ventilation rate. In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones.

Keywords: Thermal comfort, Direct Load Control, Air-conditioning, Lecture theatres

1. Introduction

As large institutional consumers universities are adversely impacted by peak electricity loads. To meet the peak demand, universities in Australia are levied substantial penalty rates. According to the network price list of a large utility company in Sydney Australia, institutional customers with a load no less than 750 MWh per annum

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will automatically be charged the KVA Demand¹ Time-of-Use Tariff (US \$9.44/KVA in 2012). Many Australian universities have exceeded the 750 MWh annual consumption thresholds and in Sydney the KVA Demand Time-of-Use Tariff is applied to the highest 30-min peak demand in the preceding 12 months. Peak demand events may only occur for a few hours in a year, but this KVA Demand Time-of-Use can represent up to 20% of the institution's total electricity costs for a whole year.

The Direct Load Control (DLC) strategy represents one of the most common approaches to managing peak electricity demand. In DLC programs, an electricity utility or aggregator has the facility to remotely shut down or cycle high-demand electrical equipment (air-conditioners, water heaters, pool pumps, etc). This paper only discusses DLC of air-conditioners (AC). Typical DLC AC control approaches include duty cycle restriction and temperature setback [2]. Duty cycle restriction involves cycling the AC compressor on and off at predetermined intervals. Under this program, the thermostat setting is maintained, but the AC compressor is only allowed to run for a predetermined time even if the set-point is not met, and then switched off (with the fan on) for a fixed period. Off cycle fraction refers to the amount of time the AC compressor will be off during an activation period. Cycling period is the time for one complete cycle of AC compressor on and off. By synchronizing and coordinating duty cycles across a large number of their customers, the utility company or the aggregator can effect substantial load shedding during peak events.

Many utility companies in USA, Australia, and Canada have conducted trials on DLC AC duty cycle restriction in residential and small business buildings in recent years (shown in Table 1). Generally speaking, these programs have reported positive results in reducing peak demands without prompting excessive complaints from customers. However to replicate the success of DLC in university lecture theatres two factors must be taken into consideration before any realistic assessments can be made. First, the occupant densities (internal loads) in a lecture theatre are much higher than in a residence. Second, the high occupant density in lecture theatres requires much higher ventilation rates. Classrooms commonly have approximately 15 times greater ventilation volumes (outdoor airflow rate per floor area) than residences [8]. The hot and frequently humid outdoor air that triggered the peak demand event in the first place will be continually introduced into the lecture theatre even when the AC compressor is cycled off, which may compromise occupants' thermal comfort during DLC events.

¹ Demand is a measure of the maximum amount of electricity being drawn from the grid over a half-hour interval. It may be measured in units of KVA or KW. Demand charges from the utility are typically levied on the customers' maximum demand for a particular time period. Depending on the network tariff, demand charges may be split into time of use periods. Furthermore, demand may be measured in rolling periods, e.g. highest demand for the last 12 months [1].

Indoor thermal environmental conditions during a DLC event depend on many factors including off cycle fraction (the amount of time the AC compressor is off during an activation period), cycling period (time for a complete cycle), cooling set-point temperature, building envelope thermal performance, ventilation rate and so on. By setting up a building and system model in building thermal simulation software, thermal environments during a DLC event can be predicted. In the literature, many building simulation studies address building energy consumption, energy conservation measures and occupant comforts in various built environments [9–13]. In relation to DLC, the extensive recent studies have mainly focused on aggregated load modelling, control strategies and prediction of demand savings [14–18]; no studies concentrating on the thermal environments and thermal comfort during DLC events have been published to date.

Peak load reduction and maintenance of comfort are two important goals for DLC programs, and DLC scenarios should be evaluated from both perspectives. However, at a micro level (single building or customer), the peak load reduction is not readily discernible due to the “rebound effect” [14, 19] which refers to the even higher peak load often occurring immediately after the load shedding period. But at a macro level (utility companies or the aggregators), a large number of participating customers with staggered DLC events for sub-groups of customers can still achieve substantial peak load reduction over and above the rebound of sub-groups. This paper does not address demand saving aspects of DLC scenarios, but rather focuses on the thermal comfort impacts on occupants at the single-building scale. It aims to present results of simulated thermal environments within a typical university lecture theatre during DLC events, as induced by various off cycle fractions, cycling periods, cooling set-point temperatures, building envelope thermal performance and ventilation rates.

2. Methodology

DesignBuilder (Version 3.2, released in May 2013), and EnergyPlus (Version 8.0.0.008, released in April 2013), were used in this simulation study. DesignBuilder was used to set up the building geometry and HVAC system configuration; EnergyPlus was then used to set up DLC control schemes and implement the simulation.

2.1. Test Building and System description

2.1.1. Building

The building under study is located in a university campus in Sydney, Australia. This two-level building has a total floor area of 2, 230 m², comprising four lecture theatres, one tutorial room, one canteen, two offices and some other auxiliary spaces. Fig. 1 illustrates the simplified Level 2 plan of the test building. The eastern and western entrances on Level 2 are the main entrances to the building. All four lecture theatres have identical

dimensions: 18.8 m length $\times$ 15.7 m width $\times$ 8.4 m height. They can be accessed either from the back doors located on Level 2 or the front doors located on Level 1 foyer. There are no external windows in this building except glass gliding doors on both Level 2 entrances and the pyramid roof skylight at the centre of Level 2 foyer. The building is normally open from 7 am to 6 pm on weekdays during semester time, though it can be extended to 9 pm or on Saturdays, depending on lecture theatre bookings. During non-semester time, lecture theatres are closed but the building common areas are open from 8 am to 4 pm.

2.1.2. HVAC Systems

The building was built in 1970 with a 200 KW natural gas boiler heating system serving four lecture theatres and the foyer areas. The chilled-water system was installed around 1980. Chilled water is supplied at 6.1 °C by a packaged reciprocating chiller set and a chilled water pump, piped to four conditioners located in level 2 plant rooms. Each conditioner, comprising two cooling coils, has a cooling capacity of 123 KW and serves a single lecture theatre. Condenser water is supplied at 29.4 °C to the chiller from a forced draught cooling tower via a condenser water pump. The chiller has a cooling capacity of 300.7 KW and COP of 3.89. It was selected based on a design where two theatres are occupied simultaneously. Chilled water cooling coils operating between 6.1/12.8 °C provide all cooling throughout the building. The design air flow rate for each lecture theatre is 4.72 m³/s and the cooling supply air temperature is 13.3 °C. The control system activates either chiller or boiler, depending on a central timer and thermostat. The cooling set-point temperature is 22 °C and the heating set-point is 20 °C. Bad practice as they may seem, these set-points are very common in Australia. Capacity control for cooling and heating output is implemented by varying the chilled or hot water flow rate using 3-way modulating control valves while fixed fan speed delivers a constant air flow rate. The tutorial room and the canteen each have their own Direct Expansion (DX) split system. Both Level 1 and Level 2 foyers are naturally ventilated.

2.1.3. Simulation Model

The rendered geometry outline of the test building generated in DesignBuilder is shown in Fig. 2. Investigations have been carried out in the test building to obtain actual internal load information, especially the occupancy schedule for model validation purposes. Though only two theatres were designed to be occupied simultaneously, observation revealed that four theatres could hold students at the same time; however the normal occupancy for each theatre was only 60–140 students. Table 2 lists internal load inputs for main spaces in the test building. For HVAC system models, the compound components of fans, cooling coils, heating coils and outdoor air mixers were represented by a four-pipe fan-coil unit in each lecture theatre in DesignBuilder model. The DX

systems in the tutorial room and canteen were represented by packaged terminal heat pumps with electric heating coils scheduled “off” at all times. The infiltration rate for the whole building was set to 1 ac/h. The ventilation control mode in Level 1 and Level 2 Foyer was set to “constant” natural ventilation through the building opening schedule.

2.1.4. Weather Data for Simulation

The test building is in Climate Zone 5 in Australia—a warm and temperate climate [20]. Although hourly based TMY2 or WYEC2 weather files from EnergyPlus were available, a nearby automatic weather station [21] provides 15-min interval real-time weather data, offering a finer resolution than the interpolated hourly weather data. Therefore, a “real day” was selected as the typical DLC event day. In preparing the EnergyPlus Weather (EPW) file, actual observations of dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, global horizontal radiation, diffuse horizontal radiation, infrared sky radiation, wind speed and wind direction were obtained from the weather station. Direct normal radiation was calculated using the following algorithms [22]:

$$Direct_{normal\ radiation} = \frac{Direct_{horizontal\ radiation}}{\sin(Solar_{height})}$$

and

$$Direct_{horizontal\ radiation} = Global_{horizontal\ radiation} - Diffuse_{horizontal\ radiation}$$

For simulation of DLC events, a five-day 15-min interval EPW file was compiled, containing the DLC event day and four preceding days. A 10-min interval EPW file was also interpolated from the 15-min one to match the needs of different cycling schemes and number of time steps in an hour for the simulation [22]. The selected DLC event day was 22nd March, 2013 based on two considerations: first, investigations in universities in Sydney suggest that the highest electricity peak demand across the whole year typically occurs in March; second, the outdoor dry bulb temperature for a real DLC event is generally above 30 °C. Fig. 3 demonstrates the weather profile on this selected DLC event day.

2.2. Model Validation

The “as built” simulation model was validated using available electricity meter readings in two separate periods – July to October, 2012, and March to June, 2013. Real-time weather data for these two periods were employed for validation. Occupancy schedules for the two validation periods were based on theatre booking information and direct observation. In July to October, 2012, the actual consumption was 128.8 MWh compared to 137.3 MWh for simulation, giving an acceptable error of 6.6% according to ASHARE Guideline 14-2002

[23]; in March to June, 2013, the actual consumption was 119.8 MWh and 110.5 MWh for simulation (error 7.7%). The simulated cooling energy consumption for each period was 25.4 MWh and 30.5 MWh respectively, which takes up 18.5% and 27.6% of the total energy consumption.

2.3. The Research Design

Five parameters have been identified to have direct influences on indoor thermal environments during DLC events. Other factors such as different HVAC systems and control modes will also have impacts, but are tangential to the research focus of this study. The five parameters and their settings are discussed below.

2.3.1. Off Cycle Fraction and Cycling Period

According to previous DLC trials and programs (e.g. programs listed in Table 1), 50% off cycle fraction and 0.5 hour cycling period are the most commonly used cycling schemes. Other off cycle fractions, such as 25%, 30%, 33%, 65%, 75%, 100% and different cycling periods, such as 1 hour have also been used. In this study, three off cycle fractions—33%, 50% and 67%, and two cycling periods—0.5 hour and 1 hour were selected for simulation.

2.3.2. Cooling Set-point Temperatures preceding DLC Events

Two levels of cooling set-point temperatures were tested, 22 °C and 24 °C. The set-point temperature of 22 °C was based on the actual cooling set-point temperature observed in the test building, whereas 24 °C was derived from PMV by solving the model for zero, which represents theoretical comfort temperature for sedentary occupants dressed in summer clothing.

2.3.3. Building Envelope Thermal Performance

The thermal properties and performance of a building envelope can commonly be represented by two parameters: the overall heat transfer coefficient (U-Value) and the thermal capacity (thermal mass). U-Value measures the ability of the building envelope to conduct heat, thus a low U-Value usually indicates high level of insulation. Thermal capacity measures the ability to store heat. The building envelope with a high thermal capacity is effective in resisting outdoor temperature fluctuation and maintaining relatively constant indoor temperature. Australian university buildings commonly adopt medium to heavy-weight constructions with relatively high thermal capacity, such as concrete, bricks, etc. However, the insulation conditions of these buildings can vary significantly according to the years of construction. For this simulation, two levels of building envelope thermal performance typical for Australia's university building stock were selected. One is the original test building fabric for external walls and roofs, representing the uninsulated 1970's building with relatively high thermal capacity; the other one is selected from the "Best practice wall, heavyweight" and "Best

practice flat roof (no ceiling), heavyweight” in the DesignBuilder building construction database, representing a well-insulated new building with high thermal capacity. Detailed building fabric layers and corresponding U-Values are listed in Table 3. Thermal properties of the main materials used in the simulation are listed in Table 4. Internal building specifications remain in the “as built” condition across all of the project’s simulation scenarios.

2.3.4. Ventilation Rates

Two levels of ventilation rates were studied. According to Australian Standard 1668.2—1991 [25], the minimum outdoor airflow rate for classrooms serving students over 16 years of age where an air cleaning unit is not provided is 10 L/s/person. Another level of ventilation rate for simulation was the 50% increase of the minimum level, which is 15 L/s/person.

To summarise, simulation scenarios in this study combined 3 off cycle fractions, 2 cycling periods, 2 cooling set-point temperatures, 2 envelope thermal performance levels and 2 ventilation rates shown in Table 5, yielding 48 simulation cases. Lecture Theatre 2 (highlight in white in Fig. 1) was selected as the test bed of the DLC event simulation since it is located in the north-west of the building, representing a “worst case” scenario in the late Australian summer afternoon. The DLC event lasted for 3 hours from 2 pm to 5 pm. It was assumed that Lecture 2 held 130 students; the lighting load was 3 KW and equipment load 0.6 KW. Internal loads and schedules for other lecture theatres or spaces in the building remain the same as in the validation model described above. Direct load control was imposed on the original HVAC systems by setting up a cycling schedule to the chilled water loop. Assumptions for thermal comfort simulation are: the clo value for all occupants is 0.5 (0.4 for clothing and 0.1 for chairs). The Metabolic Rate is 1.2 Met for sedentary occupants reading and typing. The indoor air speed is the default value in DesignBuilder—0.137 m/s.

3. Results and Discussions

3.1. Thermal Environment and Comfort during a DLC Event

To evaluate the thermal environments during a DLC event, the mean air temperature, zone Mean Radiant Temperature (MRT), zone operative temperature and zone air Relative Humidity (RH) have been plotted from EnergyPlus. The widely used thermal comfort index—Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) have also been plotted to evaluate thermal comfort impacts of the DLC event.

Fig. 4 demonstrates thermal environment parameters for a DLC scenario with 50% off cycle fraction, 0.5 h cycling period, 22 °C cooling set-point temperature, good building envelope thermal performance and ventilation rate 10 L/s/person. Values were plotted every 15 minutes from 13:30 to 17:30, which was half hour before the DLC event to half hour after it. All four parameters have saw-tooth profiles. Before the event starts,

the mean air temperature settled near the cooling set-point temperature 22 °C. When the cooling was off, it drifted to around 26 °C in 15 minutes, and then came back to about 22 °C when cooling was back on. The MRT was about 2 °C higher than the mean air temperature before the event probably because of direct sunlight being cast on the western walls and roof. During the event, the fluctuation of MRT also lagged behind the mean air temperature for about 15 minutes and reached around 26 °C at peak. The operative temperature was the average of the mean air temperature and the MRT and ranged from 23 °C to 25.5 °C during the event.

Regarding the RH, it was above 80% when cooling was on and dropped to 67% when cycled off. Although the simulated RH seems to be high in an air-conditioned building, several studies [8, 26, 27] have provided evidence that high humidity problem is very common in school buildings during hot and humid weather, partly due to the high occupant density which requires high ventilation rates, and partly due to the poor dehumidification capability of commonly used AC systems in schools. According to [8], if there is no latent cooling or internal moisture generation, the room RH would be 85% if the outdoor dewpoint temperature is 21 °C and the room temperature is 24 °C. It also points out that for chilled water AC units with constant volume fan and modulating chilled water valve (the control system in this case), as the cooling load diminishes, the flow of chilled water to the coil is reduced and the coil temperature rises, thus the ability of the coil to remove water vapour from the air declines and eventually disappears (at about 50% load factor). In this case, the chiller is oversized (the calculated cooling load is about 180 KW while the actual cooling capacity of the chiller is 300 KW). Besides, field measurements in October (very dry season in Sydney) have shown that the RH could be higher than 70% when the lecture theatre was populated with about 100 students. Based on above facts, the high humidity in the simulation results seems to be plausible. To ameliorate this situation, commonly adopted methods include the automatic fan-speed adjustment or installing a Dedicated Outdoor Air System (DOAS); both could enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events.

Fig. 5 shows the PMV/PPD index values during the DLC event. Before the event starts, PMV fixed at -0.6, a little below the recommended comfort range of -0.5—+0.5 by [24]. It indicates that the cooling set-point temperature of 22 °C, the common practice in air-conditioned buildings in Australia, is somehow low for sedentary occupants dressing in typical summer clothing. Along with the temperature rising when the cooling cycles off, PMV increased to around 0.4, still within the comfort range. PPD maintained around 13% when cooling was on and dropped to about 7% when cooling was off, indicating that in this DLC scenario, cycling on

and off AC system at 15-min intervals from 22 °C has increased occupants' thermal comfort by mitigation of AC overcooling rather than decreasing comfort.

3.2. Effects of Different Parameters on Thermal Environments during DLC Events

Figs. 6-9 illustrate operative temperature profiles simulated from various parameter values during DLC Events. In each figure, two parameters vary while the other three parameters were held constant. Figs. 6-9 demonstrate that all 5 parameters analysed had impacts on occupied zone thermal environments during DLC events. In order to find out which parameter had relatively larger influence, the maximum operative temperatures in all 48 simulation scenarios were analysed in relation to the levels of input parameters in question. One-way ANOVA test revealed that there was a significant difference between impacts of different parameters ($p < 0.001$). *Post hoc* procedure (Games-Howell) [28] was carried out to identify significantly different pairwise comparisons (Table 6). Across the range of parameter values tested which represent typical Australian university lecture theatre settings, the impacts of cycling period variations were significantly larger than impacts of cooling set-point temperature differences and building envelope thermal performance levels, which were in turn significantly greater than impacts of ventilation rate variations. Obviously the magnitude of impacts of various input parameters relates to the range of values tested. All parameters tested covered reasonable and representative ranges for the Australian university sector. Any parameter value outside this range might result in the relative impacts being amplified. In addition, other factors which include HVAC system types, cooling loads and control modes can also be expected to have an impact. To make a general conclusion, in typical Australian university lecture theatres, off cycle fractions, cycling periods and cooling set-point temperatures have relatively larger influences on occupied zone thermal environments during DLC events compared to building envelope thermal performance levels and ventilation rates.

3.3. Thermal Comfort Impacts of DLC Events

Most contemporary thermal comfort standards are specified as an acceptable range of the relevant comfort index. They also stipulate that large temperature fluctuations not under the direct control of individual occupants should be avoided so as to keep thermal environment relatively static. However, above analysis show that duty cycle restriction in a DLC event will cause repeated rises and falls in air temperature, MRT and RH, creating dynamic thermal environments. Since the PMV/PPD model was derived in a controlled climate chamber under steady conditions, it might not be fully appropriate to assess thermal comfort impacts during DLC events, so in this study it serves merely as indicative comfort performance criterion. The actual thermal comfort impacts of

DLC events can only be obtained from replicating simulated DLC events within climate chamber experiments with human subjects or in actual field studies.

3.3.1. ASHRAE 55-2013 Permissible and Simulated Temperature Changes for Temperature Drifts

ASHRAE 55-2013 (5.3.5 Temperature Variations with Time) requires that for cyclic variations with a period not greater than 15 minutes, the maximum allowable peak-to-peak variation in operative temperature is 1.1 °C [24]; for temperature ramps and drifts, the maximum operative temperature change allowed during a period of time is shown in Table 7. Cyclic variations with a period greater than 15 minutes are assessed with the ramps or drifts criteria [24]. Since the cycling periods for all DLC events under study are longer than 15 minutes, they should be treated as temperature drifts and should comply with the requirement in Table 7. Results indicate that simulated operative temperature changes within specific time periods during DLC events all exceeded the ASHRAE 55- 2013 limits (see Table 7). Simulation results were grouped according to cooling set-point temperatures. Duty cycle restriction in a DLC event causes temperature fluctuations that exceeded the ASHRAE standard.

3.3.2. PMV/ PPD Model as the Thermal Comfort Index

As is stated in ASHRAE 55-2013, PMV/PPD is widely used to determine the requirements for thermal comfort in occupied spaces. It recommends that PMV should be held within the range of -0.5 to +0.5 and PPD within 10% [24]. Fig. 10 illustrates a boxplot of maximum PMV/PPD in 48 scenarios pooled by different values of parameters. Across all DLC scenarios, the mean of maximum PMV is 0.9 ± 0.3 (SD). The maximum PMV in only part of the lower quartile values fell below +0.5. Generally speaking, the interquartile range of maximum PMV in parameters with low-level values (such as 33% off cycle fraction, 0.5 h cycling period, good envelope thermal performance, etc.) fell between the PMV range of +0.5—+1, while the upper half of maximum PMV in parameters with high-level values (67% off cycle fraction, 1 h cycling period, poor envelope thermal performance, etc.) all exceeded +1. The mean maximum PPD in 48 scenarios is $26.2\% \pm 10.3\%$ (SD). It should be noted that the maximum PMV and PPD values during DLC events do not necessarily correspond to each other since in some cases such as the one stated in Section 3.1, the maximum PPD was achieved when AC was on and the PMV was very low due to AC overcooling. For this reason, even the lower quartile PPD values exceeded 10% (shown in Fig. 10). Fig. 10 also reveals that most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD methods specified in ASHRAE 55-2013.

Though PMV/PPD may not be strictly appropriate for DLC events, previous laboratory studies on temperature transients have reported that moderate operative temperature changing rate of lower than 0.5 °C/h has no

influence on thermal sensation or thermal comfort (acceptability) than in steady states [29, 30]; for rate of change greater than 1 °C/h, subjects' thermal sensation generally agrees well with predicted by PMV model (tested up to ± 5.0 °C/h) [31–35], but thermal acceptability tends to shrink in the cooler side [31–33]. However, there is no consistent conclusion on the limit of the temperature changing rate within which PMV/PPD will be valid. Still, the suitability of PMV/PPD model for application to DLC events needs to be tested in laboratory experiments and field studies.

3.3.3. Optimizing DLC Algorithms for University Lecture Theatres

The preceding analysis reveals that the majority of DLC scenarios tested had adverse thermal comfort impacts on the occupants. DLC scenarios with higher off cycle fraction, longer cycling period, higher cooling set-point temperature, poorer building envelope thermal performance and higher ventilation rate will induce more occupant thermal discomfort during DLC events. Although a common practice in previous DLC programs, a standard or universal DLC algorithm for all participating premises will not guarantee universally acceptable thermal environments, and run the risk of increased override rates [2, 5]. In order to achieve acceptable thermal comfort outcomes, DLC algorithms must be applied judiciously and customized to the specific building.

Selection of DLC algorithms in university lecture theatres or any other classroom buildings should take into account cooling set-point temperatures, building envelope thermal performance as well as ventilation rates.

Usually in an existing building, the construction type and ventilation rate are already set. If the buildings have relatively poor envelope thermal performance and high ventilation rates, only conservative DLC algorithms with low off cycle fraction, short cycling period and low cooling set-point temperature should be selected; if the buildings have relatively good envelope thermal performance and moderate ventilation rate, more ambitious algorithms can be considered for higher peak demand reduction. However, cycling schemes combining 67% off cycle fraction with 1 h cycling period are not recommended for lecture theatres at any time.

Comparison of 24 pairs of simulation cases with the same off cycle fraction, set-point temperature, building envelope thermal performance and ventilation rate, but different cycling periods (0.5 h vs. 1 h) using the independent *t*-test revealed that the difference in maximum PPD during DLC events, -11.6%, was significant at $p < 0.001$, representing a large-sized effect (Cohen's $d = 1.22$). It suggested that, all else being equal, especially the off cycle fraction which determines the amount of load shedding, shorter cycling period DLC scenarios have less adverse thermal comfort impacts than longer ones. This could be another way of optimizing DLC algorithms. However in practice, cycling periods must not be so short as to cause compressor failures and inefficiencies [14]. The prevailing 0.5 h cycling period in previous DLC programs can serve as an ideal value.

4. Conclusions and Suggestions

By simulating a typical university lecture theatre in DesignBuilder and EnergyPlus, this study has explored thermal environments and thermal comfort impacts of DLC events induced by various off cycle fractions, cycling periods, cooling set-point temperatures, building envelope thermal performance and ventilation rates.

The following conclusions can be drawn from the present study:

- During DLC events, the air temperature, mean radiant temperature and relative humidity all fluctuate with the AC on and off, forming saw-tooth profiles. Though simulation results suggest high relative humidity, according to other studies, high humidity problems are very common in school buildings with poor dehumidification capability but located in hot and humid climate zones. Use of variable speed fans or Dedicated Outdoor Air Systems can enhance the dehumidification capability of the HVAC system and maintain lower indoor RH during DLC events, which will offset the adverse thermal comfort impacts of DLC due to high RH.
- All 5 parameters tested in this study have impacts on thermal environments during DLC events. Under tested conditions which represent typical Australian university lecture theatre settings, off cycle fractions, cycling periods and cooling set-point temperatures have relatively larger influences compared to building envelope thermal performance and ventilation rates.
- Simulation results show that DLC scenarios do not comply with the limits on temperature ramps and drifts specified in ASHRAE 55-2013. Most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD method indicated in ASHRAE 55-2013. However, the PMV/PPD index is an indicative-only thermal comfort index. Subjects' actual thermal comfort impacts of DLC events can only be obtained from laboratory experiments or field studies, which are the focus of future research by the authors.
- In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. Selection of DLC algorithms should take all influencing parameters into account and avoid disadvantageous parameter-combinations. University buildings with poor envelope thermal performance and high ventilation rate should adopt conservative DLC scenarios, while buildings with good envelope thermal performance and moderate ventilation rate can implement more radical DLC algorithms to achieve higher peak demand reduction. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones, and are therefore recommended for university lecture theatre applications.

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References

- [1] EnergyAction, Get to know your bill, <http://www.energyaction.com.au/australian-energy-market/get-to-know-your-bill/175.html>, accessed 2014-07-20.
- [2] G.H. Weller. New wave of Direct Load Control update on DLC systems, Technology, 2011, http://www.elp.com/articles/powergrid_international/print/volume-16/issue-7/features/new-wave-of-direct-load-control-update-on-dlc-systems-technology.html, accessed 2014-06-01.
- [3] Essential Services Commission of South Australia ETSA, Utilities demand management program: progress report. Essential Services Commission of South Australia, Adelaide, 2008.
- [4] PG & E, Final report: Pacific Gas and Electric SmartAC load impact evaluation, 2008, https://www.smartgrid.gov/document/final_report_pacific_gas_and_electric_smartac_load_impact_evaluation, accessed 2014-05-30.
- [5] D. Greenberg, M. Straub, Demand Response delivers positive results, Transmission & Distribution World, 2008, <http://tdworld.com/smart-energy-consumer/demand-response-delivers-positive-results>, accessed 2014-05-31.
- [6] FSC, Freeman, Sullivan & Co, 2010 Residential and small commercial Demand Response initiative and Hydro Ottawa peaksaver® small commercial pilot program evaluation (final report), June 2011, http://www.powerauthority.on.ca/sites/default/files/new_files/2010/2010%20peaksaver%20Residential%20and%20Small%20Commercial%20Demand%20Response%20Load%20Impact%20Evaluation.pdf, accessed 2014-05-31.
- [7] Perth Solar City Annual Report, 2012, http://www.westernpower.com.au/documents/smartGrid/PSC_-_2012_ANNUAL_REPORT_-_FINAL_FOR_DISTRIBUTION_%28LO-RES_18.pdf, accessed 2014-05-31.
- [8] J. Cummings, C. Withers, Energy efficient strategies to control relative humidity in schools, <http://www.southernbuildings.org/resources/pdfs/EnergyEfficientStrategies.pdf>, accessed 2014-05-31.

- [9] O. Alhaj Hasan, D. Defer, I. Shahrour, A simplified building thermal model for the optimization of energy consumption: Use of a random number generator, *Energy and Buildings* 82 (2014) 322–329.
- [10] A. Boyano, P. Hernandez, O. Wolf, Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations, *Energy and Buildings* 65 (2013) 19–28.
- [11] J.W. Moon, S.-H. Han, Thermostat strategies impact on energy consumption in residential buildings, *Energy and Buildings* 43 (2011) 338–346.
- [12] W. Guo, D.W. Nutter, Setback and setup temperature analysis for a classic double-corridor classroom building, *Energy and Buildings* 42 (2010) 189–197.
- [13] Y. Pan, R. Yin, Z. Huang, Energy modelling of two office buildings with data centre for green building design, *Energy and Buildings* 40 (2008) 1145–1152.
- [14] W. Zhang, J. Lian, C.-Y. Chang, K. Kalsi, Aggregated modelling and control of air conditioning loads for Demand Response, *IEEE Transactions on Power Systems* 28 (2013) 4655–4664.
- [15] S. Banash, H. Fathy, Modelling and control insights in to demand-side energy management through setpoint control of thermostatic loads, In American Control Conference, June 2011.
- [16] P. Xu, P. Haves, M. A. Piette, J. Braun, Peak demand reduction from pre-cooling with zone temperature reset in an office building, Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory, 2004, <http://escholarship.org/uc/item/1205612d>, accessed 2014-06-01.
- [17] N. Khaled, M. Krarti, Impact of precooling control on reducing electrical peak demand for commercial buildings in Tunisia, in proceedings of ASME 2007 Energy Sustainability Conference, pp.565.
- [18] R. Yin, S. Kiliccote, M. A. Piette, K. Parrish, Scenario analysis of peak demand savings for commercial buildings with thermal mass in California, 2010 ACEEE Summer Study on Energy Efficiency in Buildings, <http://eetd.lbl.gov/sites/all/files/lbnl-3636e.pdf>, accessed 2014-05-31.
- [19] S. Borlase, *Smart Grids: infrastructure, technology, and solutions*, Taylor & Francis, 2012.
- [20] National Construction Code Series Volume One, Building Code of Australia Class 2 to Class 9 Buildings, Australian Building Codes Board, Canberra, Australia, 2013.
- [21] Macquarie University Automatic Weather Station, <http://aws.mq.edu.au/>, accessed 2014-05-31.
- [22] Auxiliary EnergyPlus Programs: extra programs for EnergyPlus, Version 8.0, April 2013.
- [23] ASHRAE Guideline 14-2002, Measurement of energy and demand savings, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2002.

- [24] ASHRAE Standard 55-2013, Thermal environmental conditions for human occupancy, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2013.
- [25] Australian Standard 1668.2—1991, The use of mechanical ventilation and air-conditioning in buildings Part 2: Mechanical ventilation for acceptable indoor-air quality. Standards Australia, April 1991.
- [26] J.C. Fischer, Optimising IAQ, humidity control, and energy efficiency in school environments through the application of desiccant-based total energy recovery systems, in Proceedings of IAQ 96, <http://legacy.library.ucsf.edu/documentStore/t/g/h/tgh67c00/Stgh67c00.pdf>, accessed 2014-06-01.
- [27] R.G. Morse, P. E. Haas, D. E. Zehnter, Causes and effects of high humidity in South Florida schools, in Proceedings of the fifth international conference on thermal performance of the exterior envelopes of whole buildings, 2007, http://web.ornl.gov/sci/buildings/2012/2007%20B10%20papers/010_Morse.pdf, accessed 2014-05-31.
- [28] L.E. Toothaker, ed., Multiple comparison procedures, No. 89, Sage, 1993.
- [29] I.D. Griffiths, D.A. McIntyre, Sensitivity to temporal variations in thermal conditions, *Ergonomics* 17(1974) 499–507.
- [30] L.G. Berglund, R.R. Gonzalez, Application of acceptable temperature drifts to build environments as a mode of energy conservation, *ASHRAE Transactions* 84 (1978) 110–121.
- [31] H. N. Knudsen H, R. J. de Dear, J. W. Ring, T. L. Li, T. W. Puntener, P. O. Fanger, Thermal comfort in passive solar buildings, Final report to the Commission of the European Communities, Directorate-General for Science, Research and Development, Technical University of Denmark, 1989.
- [32] J. Kolarik, J. Toftum, B.W. Olesen, A. Shitzer, Human subjects' perception of indoor environment and their office work performance during exposures to moderate operative temperature ramps, in Proceedings of Indoor Air 2008, pp.429.
- [33] J. Kolarik, J. Toftum, B. W. Olesen, A. Shitzer, Occupant responses and office work performance in environments with moderately drifting operative temperatures (RP-1269), *HVAC & R Research* 15 (2009) 931-960.
- [34] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, A.J.H. Frijns, J. Toftum, M.H. de Wit, Thermal comfort, physiological responses and performance of elderly during exposure to a moderate temperature drift, in Proceedings of Healthy Buildings 2009, pp.249.

- [35] L. Schellen, W.D. van Marken Lichtenbelt, M.G.L.C. Loomans, J. Toftum, M.H. de Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, *Indoor Air* 20 (2010) 273–283.