Control of Distributed Cooling and Ventilation Systems in Hot and Humid Climates

Markus Gwerder*[1], Bharath Seshadri[2]

1 Siemens Switzerland Ltd
Building Technologies Division
Gubelstrasse 22
Zug, Switzerland
**Corresponding author: markus.gwerder@siemens.com*

2 ETH Zurich
Architecture and Building Systems
Institute of Technology in Architecture
Zurich, Switzerland

ABSTRACT

In the research project 3for2 Beyond Efficiency, low-exergy distributed cooling and ventilation systems for application in the tropics are designed and tested in a demonstrator building in Singapore. The HVAC system designed consists of passive chilled beams for sensible cooling, fan coil units for latent cooling and dedicated outdoor air handling systems for IAQ control. The design reduces building space requirements due to less ventilation equipment. Optimally, this may allow building 3 floors in the conventional space of 2 with equal occupant floor-to-ceiling heights, hence the name 3for2. In addition, it proposes to improve comfort of occupants and increase overall building energy efficiency by a factor of two. The demonstration site is a 550 m^2 test case of the 3for2 concept in the administrative offices of United World College South East Asia (UWCSEA), an international school in Singapore. The demonstration building was commissioned by end of 2015 and has been running in regular operation since beginning of 2016.

This paper reports on the basic control strategy implemented and on key elements of the building control. A simulation model representing one zone of the demonstrator building including its control is presented and calibration results using measured data are given. In a simulation case study using the calibrated model, results for two selected building locations (Singapore and New Orleans) were produced. The cases contain different control strategies, different comfort settings as well as different HVAC systems including a conventional air-based only system. These cases allow assessing the benefit of advanced control, but also put it into context by comparison to cases with different comfort requirements or HVAC systems. All cases were assessed based on comfort and electrical energy consumption for HVAC operation.

In practical application, the implemented control strategy has been able to successfully achieve a high comfort level in an energy efficient way. In simulations, results show that electrical energy use for HVAC varies strongly for the different cases – for the Singapore location from 26% lower to 38% higher than base case – while for most cases comfort settings can be achieved tightly. The simulations indicate that presence detectors and in particular IAQ measurements allow for substantial increase in terms of energy efficiency while still maintaining comfort settings. In hot and humid climates such as in Singapore, morning start-up dehumidification and cooling causes a significant part of whole HVAC energy consumption. Optimized start-up cases are shown to contribute significantly to an energy efficient operation. Both experience from demonstrator operation as well as simulation results substantiate that control is particularly important for the investigated HVAC system since the different subsystems for cooling, dehumidification and IAQ control have to be coordinated in order to achieve the desired performance.

KEYWORDS

Building control, smart ventilation, energy efficiency, cooling and dehumidification

1 INTRODUCTION

Climate change and urbanization are the two main drivers for limited space and resources in future cities, with many of those cities situated in hot and humid climate zones. A significant change in building design approach can help answering these challenges. The “3for2” design concept for buildings in hot and humid climates is such an approach that reduces space needs for HVAC systems dramatically compared to conventional approaches, while still providing energy services in an efficient, architecturally-appealing manner (Schlueter, 2016). The three main 3for2 design principles are (i) the decoupling of sensible and latent cooling into independent air-conditioning systems, (ii) the decentralization of ventilation and latent cooling equipment, and (iii) the integration of decentralized air conditioning equipment and distribution pipe/ductwork into a building’s floor and façade structures. Key components of the concept are the water based cooling systems (e.g. chilled ceilings) for sensible heat removal, compact fan coil units optimized for latent heat removal and underfloor ventilation systems (possibly with air ducts integrated in slab).
The 3for2 office space is a pilot implementation of the 3for2 concept, see (Rysanek, 2015a) for a simulation based design study of the demonstrator system. It is part of the High School building of United World College South East Asia's (UWCSEA) Dover campus in Singapore. The space is located on the 3rd floor of the building and covers approximately 550m^2 of that floor; see Figure 1. Since December 2015, the space is occupied by UWCSEA’s management staff. (Pantelic, 2017) reports on the satisfaction of occupants regarding indoor environmental quality in the space. Four distributed, façade-integrated air handling units (AHU) supply the 13 rooms with conditioned air; each AHU consists of one dedicated outdoor air system (DOAS) and one recirculation fan coil unit (FCU). Sensible cooling loads are removed by passive chilled beams (PCB).

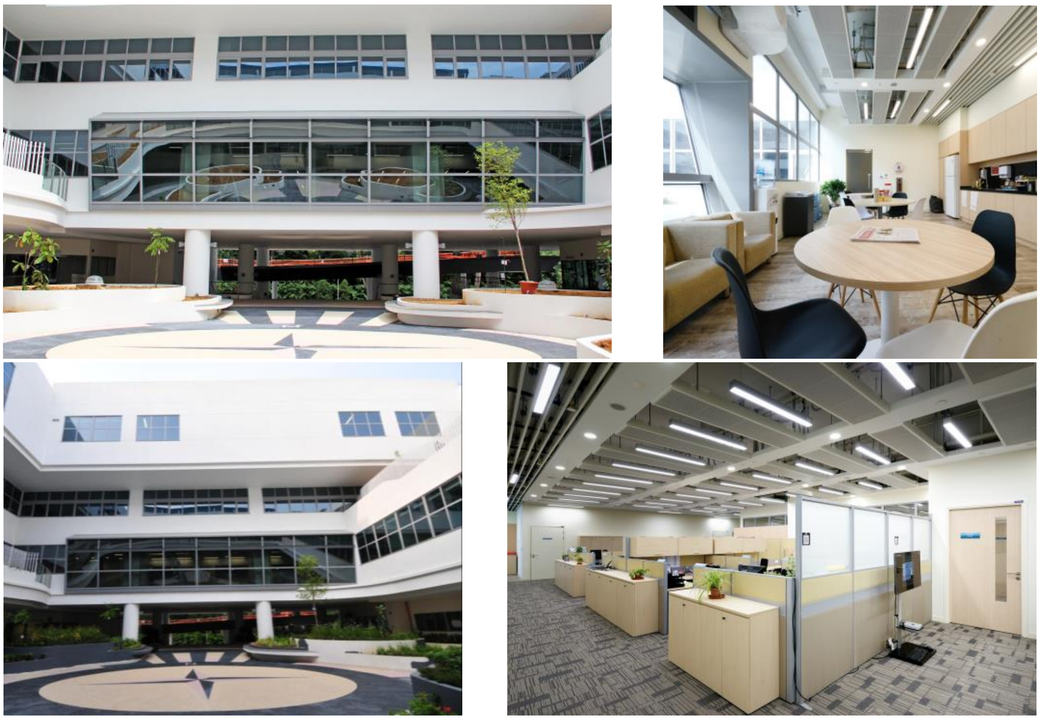

Figure 1: Demonstrator building containing the 550m^2 3for2 space (left),
3for2 pantry and open office (right) (*photos: Future Cities Lab*)

The control of a system such as the pilot implementation is required to be robust and reliable while achieving comfort in an energy efficient way. The investigated control follows a strict demand controlled approach for ventilation, cooling and dehumidification. In particular demand controlled ventilation has been studied extensively in the past, see e.g. (Apte, 2006). The paper presents a case study that allows assessing the control performance. The focus is on different control cases; however – to put the results into context – also different comfort and HVAC system cases are included. It is a simulation case study, but based on models calibrated by measurements. A similar case study could also have been executed in the demonstrator building, but this would have some significant limitations and drawbacks: Sequential experiments, considerable setup effort, difficult comparison because of different (unmeasured) disturbances in internal and external loads (e.g. occupants, equipment, weather conditions, etc.).

2 METHODS

2.1 Modeling and Calibration

The scope of the paper is limited to modeling and simulation of one particular zone within the 3for2 space. A simplified plant scheme of the zone is shown in Figure 5. The modeled zone has a floor area of 106 m^2 and contains 1 AHU and 5 rooms that are all used as offices. The model is implemented in MATLAB/Simulink. It is based on existing model components for multi-zone building models (Gao, 2007) as well as models adopted from building simulation software (TRNSYS 17, 2014). For fans and PCBs, data-driven models derived from demonstrator building measurements were used. In simulation, the exact same control functions as applied in the real Siemens building automation system were implemented.
Firstly, the model was validated by comparison to a model for the same zone implemented in TRNSYS. (Rysanek, 2015b) describes the TRNSYS modeling for a similar single room 3for2 zone. Secondly, the model was calibrated using measured data from the demonstrator building. Example building and AHU model validations are shown in Figure 2 and Figure 3 respectively. Generally, the model can reproduce measured temperatures and cooling powers very well. For room air humidity and CO_2 concentration, the model accuracy is lower. Since the case study results shall be representative for buildings such as the 3for2 demonstrator building (but not exactly reproduce the particular building), the model's accuracy is sufficient for the purpose of the case study.

2.2 Base Case Control Strategy

The control strategies investigated in this paper are built from proven and robust control elements using only measurement information that is typically available. Additional measurements installed for research purposes only are not processed by the control strategies. The investigated control strategies are all based on a base case strategy using different settings and configurations. Therefore, we here describe the base case for control and report on changes in other cases below. The base case strategy also represents closely what is implemented in the real building since June 2016. The base case control strategy is structured in different, largely autonomous control tasks which results in a moderate complexity control solution. A clear separation between room temperature control, room air humidity control and room air quality control is made. While the room temperature is controlled by the PCBs, the humidity is controlled by the recirculation FCUs, and the air quality is controlled by the DOAS using CO_2 concentration measurements. In order to reduce the interaction between temperature and humidity control tasks, absolute humidity instead of relative humidity is controlled. Simplified plant and control schemes for regular base case control operation are shown in Figure 4 (room temperature and room air dew point temperature based flow temperature control) and Figure 5 (room air absolute humidity and CO_2 concentration control). Error handling and subsystem interactions that do not occur during normal operation are not shown, e.g. condensation detection logic or sensible cooling support by AHU. Also, the figures only show control logic for active cold demand (which is always the case for Singapore weather), but not for no thermal demand or heat demand.

Per zone, there is a schedule that defines the comfort phases, based on which the HVAC system is operated on. After longer shut-down phases (usually during early morning hours), a start-up sequence is triggered that involves the dehumidification and flushing out of air. This happens in advance of a comfort phase to reach a target absolute humidity level. An optimum start control (OSC) algorithm learns the start-up time based on previous start-up durations and outside air absolute humidity levels. The OSC algorithm used is of a similar class as the one described in (Garcia-Sanz, 1994), but applied to humidity instead of temperature. Similarly, another OSC algorithm for room temperature controls the PCB start-up.

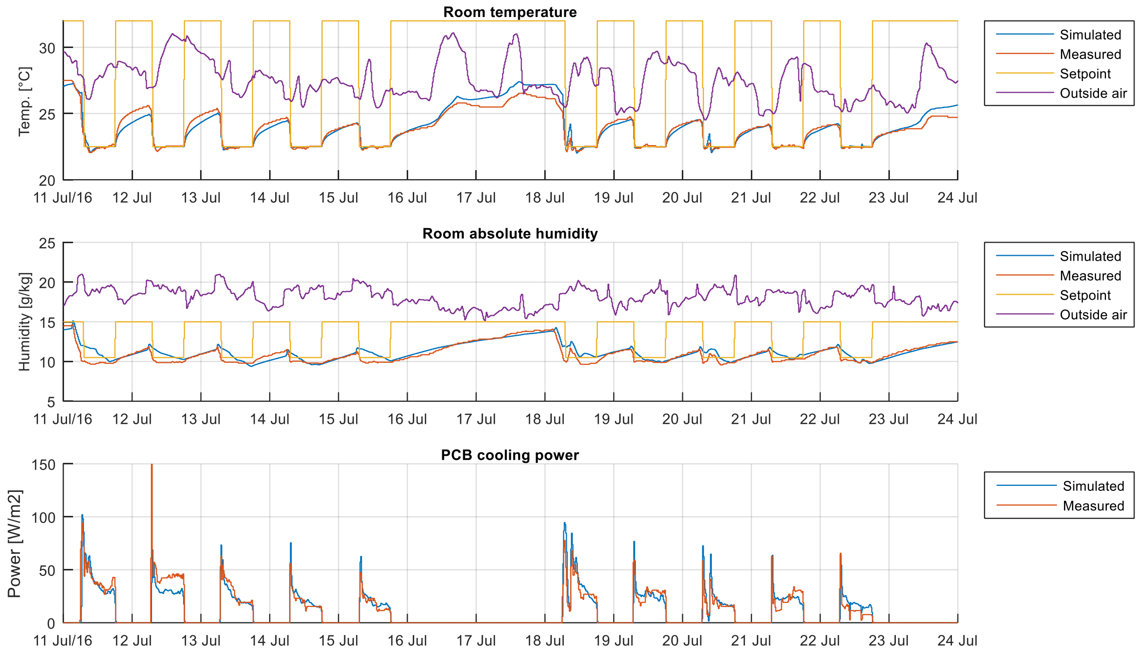

Figure 2: Building model validation example; two weeks during July 2016 for one room of the zone

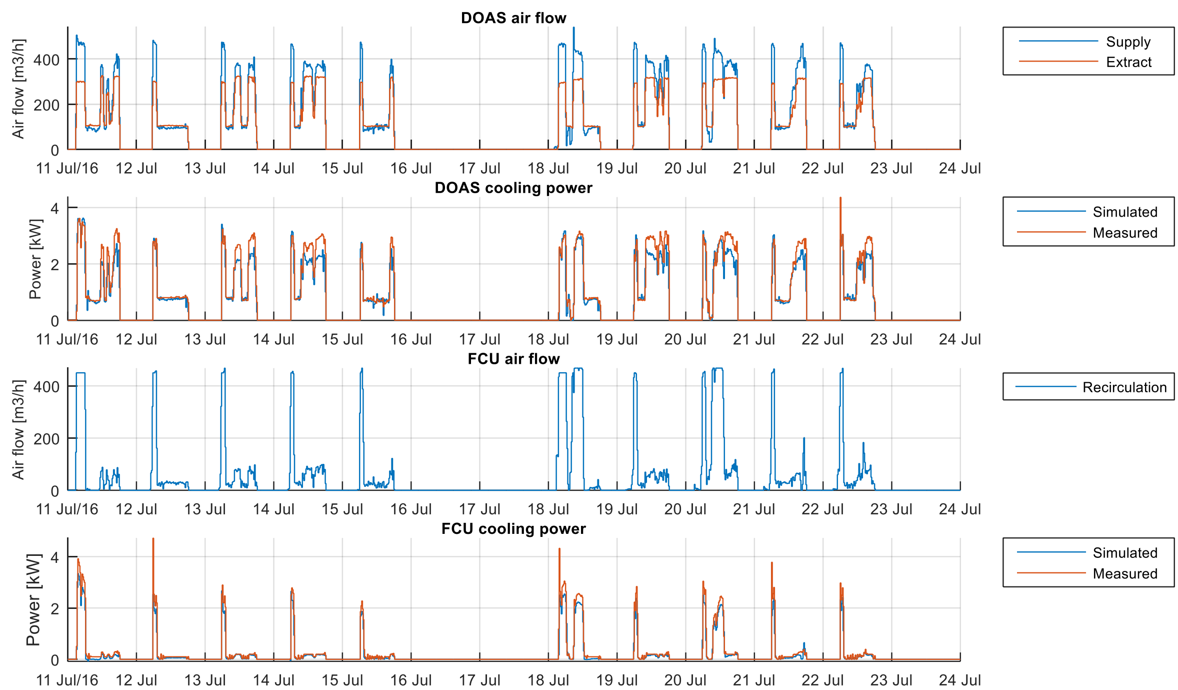

Figure 3: AHU model validation example; two weeks during July 2016 for air handling unit

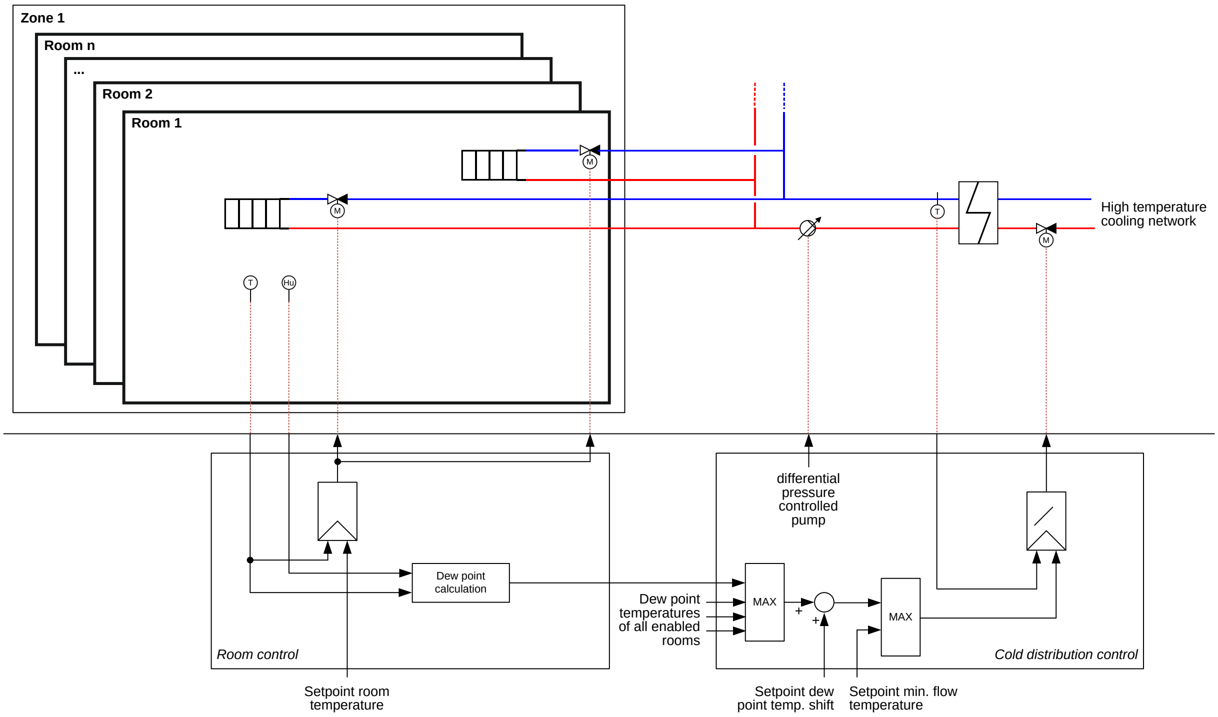

Figure 4: Simplified plant and control scheme for base case room temperature control

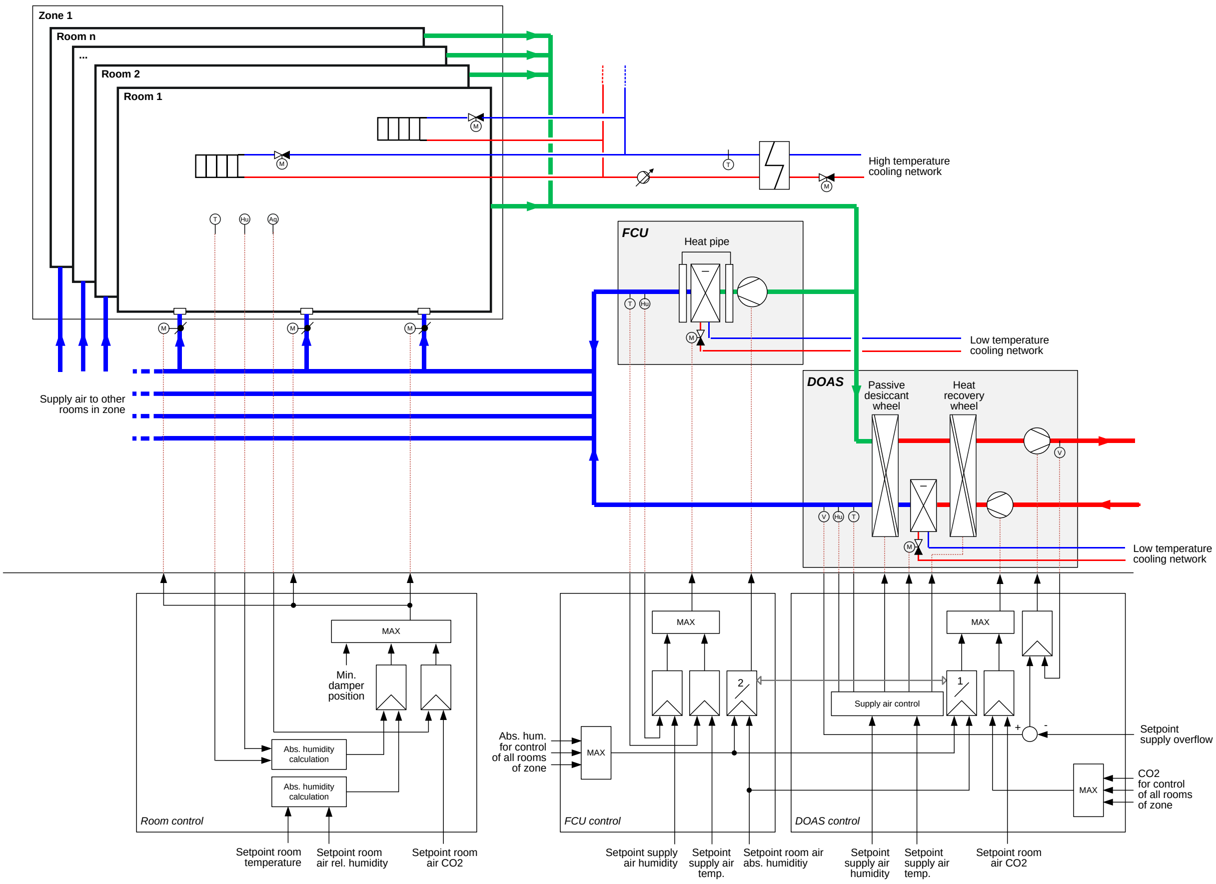

Figure 5: Simplified plant and control scheme for base case room air humidity and CO_2 concentration control

2.3 Simulation Case Study Set-Up

For all cases, Meteonorm weather data for either Singapore or New Orleans was used. The New Orleans location was selected since it has a comparable climate to Singapore during summer, but unlike Singapore has a distinctively cooler climate during winter. Therefore, a similar building and HVAC system – with the addition of using PCBs for moderate heating action – is suitable for New Orleans, too. The simulated time span is March 1st till June 1st, using internal gains based on measured presence in the 3for2 space for the same time period in 2016. In terms of control, the base case configuration is similar to 3for2 space implementation: During comfort phases, set points of 22.5°C for room temperature cooling, 21°C for room temperature heating, 10.5 g/kg room air absolute humidity and 800 ppm room air CO_2 concentration were used. These values correspond to the actual settings in the 3for2 demonstrator building which have been adjusted based on user feedback.

Table 1 gives an overview about the presented case study. There are cases that only feature changed comfort settings (2-9). Some cases include a presence-based switch between pre-comfort and comfort settings (10, 11, 23, 24). Several cases define variations of start-up settings (12-19) and flow tracking settings (20-22). Combinations of the most energy efficient settings are compiled in cases 23 & 24. Cases 25-27 represent different HVAC systems or instrumentation and are included to compare to systems without CO_2 sensors, without energy recovery or to a conventional air based only HVAC system.

Electrical energy for cold generation and distribution is derived from the cold demand using a constant chiller plant energy efficiency rate of 5 both for PCB and AHU cold demand. In an ideal low-exergy system, a low-lift chiller having a significantly higher energy efficiency rate would be used for PCB cold generation for the PCBs (Seshadri, 2017). For the New Orleans cases, heat is assumed to be produced by a heat pump with a constant heat generation coefficient of performance of 4.

Table 1: Simulated cases (columns CO_2 and Psc. indicate CO_2 and presence meas. required, respectively)

Nr	Case Description	Remark	CO_2	Psc.
1	Base case control strategy (comfort phases Mon-Fri 7am-6pm)	-	x	
2	Extended comfort phases (comfort phases Mon-Fri 6am-7pm)	enhanced comfort	x	
3	Comfort on weekends (comfort phases Mon-Sun 7am-6pm)		x	
4	Comfort 24/7 (always comfort)		x	
5	Wider temperature comfort range (2K wider range)	reduced comfort	x	
6	Higher CO_2 comfort setpoint (200ppm higher comfort setpoint)		x	
7	Higher humidity comfort setpoint (1g/kg higher comfort setpoint)		x	
8	Higher temperature comfort range (1.5K higher thermal comfort setpoints)	shifted comfort	x	
9	Lower temperature comfort range (1.5K lower thermal comfort setpoints)		x	
10	Presence dependent comfort (presence dependent switch to comfort)	presence based comfort	x	x
11	Wider temperature pre-comfort range (2K wider range)		x	x
12	Startup fan speed 100%	varied start-up	x	
13	Startup fan speed 50%		x	
14	Startup fan speed 35%		x	
15	Startup fan speed 20%		x	
16	Heating/cooling startup with pre-comfort target		x	
17	Dehumidification startup with higher humidity target setpoint		x	
18	Cooling startup begin when humidity high (no OSC for room temperature)		x	
19	Constant dehumidification duration (no OSC for room temp. and humidity)		x	
20	DOAS flow tracking difference setpoint 0 l/s (balanced flow)	varied flow tracking	x	
21	DOAS flow tracking difference setpoint 30 l/s (unbalanced flow)		x	
22	DOAS flow tracking difference setpoint 50 l/s (heavily unbalanced flow)		x	
23	Energy efficiency combination with equal comfort	maximum energy efficiency	x	x
24	Energy efficiency combination with lower comfort		x	x
25	High DOAS min fan speed (no CO_2 measurements)	constant outside air volume		
26	No energy recovery (HVAC system without energy recovery)	alternative HVAC systems	x	
27	Conventional system (central AHU with mixed air dampers)		x	

3 RESULTS

3.1 Singapore Location

For the Singapore location cases, total HVAC electrical energy consumption ranges from 7.0 to 13.0 kWh/m^2 for the simulated three months, see Figure 6 and Table 2. The base case total electricity consumption is 9.4 kWh/m^2 which splits into 5.1 kWh/m^2 cold for PCB, 2.5 kWh/m^2 cold for AHU and 1.7 kWh/m^2 fan energy. In terms of comfort regarding temperature, humidity and air quality, the according set points are maintained well for all cases. The only major exception is the violation of the CO_2 setpoint in individual rooms by the conventional system case because the system's VAV dampers are controlled to meet only the room temperature set point. Thus, the results of this paper can focus on the energy efficiency comparison of the cases – comfort performance is not reported here.

Start-up settings cases (12-19) mainly differ in fan energy consumption. Reducing start-up fan speeds from the base case value of 70% to 20% decreases fan energy consumption by 27% while cold electrical energy consumption is practically unchanged. Using PCBs to support dehumidification during start-up (case 17) results in a performance close to the base case performance – however, this solution provides a somewhat better comfort during start-up and has advantages if PCB cold generation was more efficient (by using a low-lift chiller).

Results for the flow tracking cases (20-22) show large differences in AHU cold consumption. Increasing the flow tracking set point from the base case value of 10 l/s to 50 l/s increases AHU electrical cold consumption by 100% which by far cannot be compensated by the decrease of fan consumption.

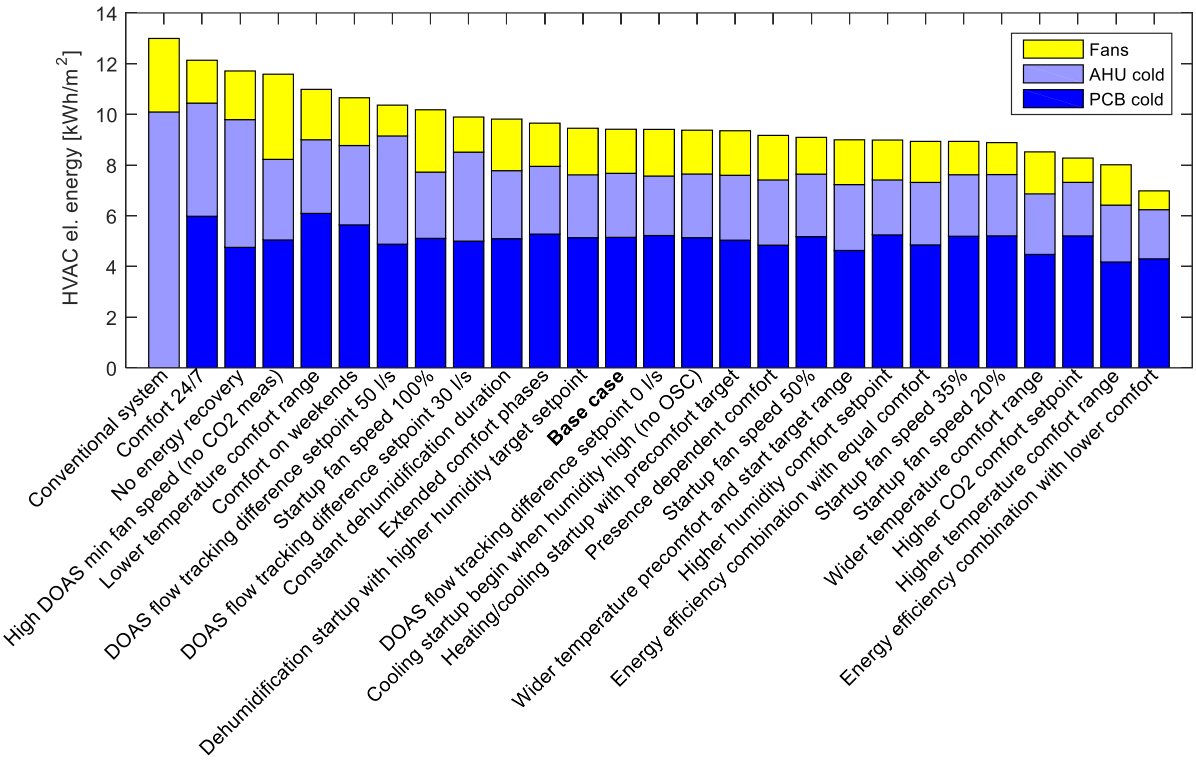

Figure 6: Case study results for (and sorted by) HVAC electrical energy consumption, location Singapore

3.2 New Orleans Location

For the New Orleans cases, total electrical energy consumption ranges from 2.3 to 5.7 kWh/m^2 for the simulated three months, see Figure 7 and Table 2. The base case total electricity consumption is 4.2 kWh/m^2 which splits into 0.6 kWh/m^2 heat for PCB, 1.7

kWh/m^2 cold for PCB, 0.7 kWh/m^2 cold for AHU and 1.3 kWh/m^2 fan energy. As for the Singapore cases, all cases perform well in terms of comfort. Although the simulations were not executed for whole years, scaled-up results for the Singapore cases come close to whole year simulation results since the simulated weather is representative for the whole year. This is not the case for the New Orleans cases: In the simulated spring time period, there is a transition from heat demand to cold and dehumidification demand.

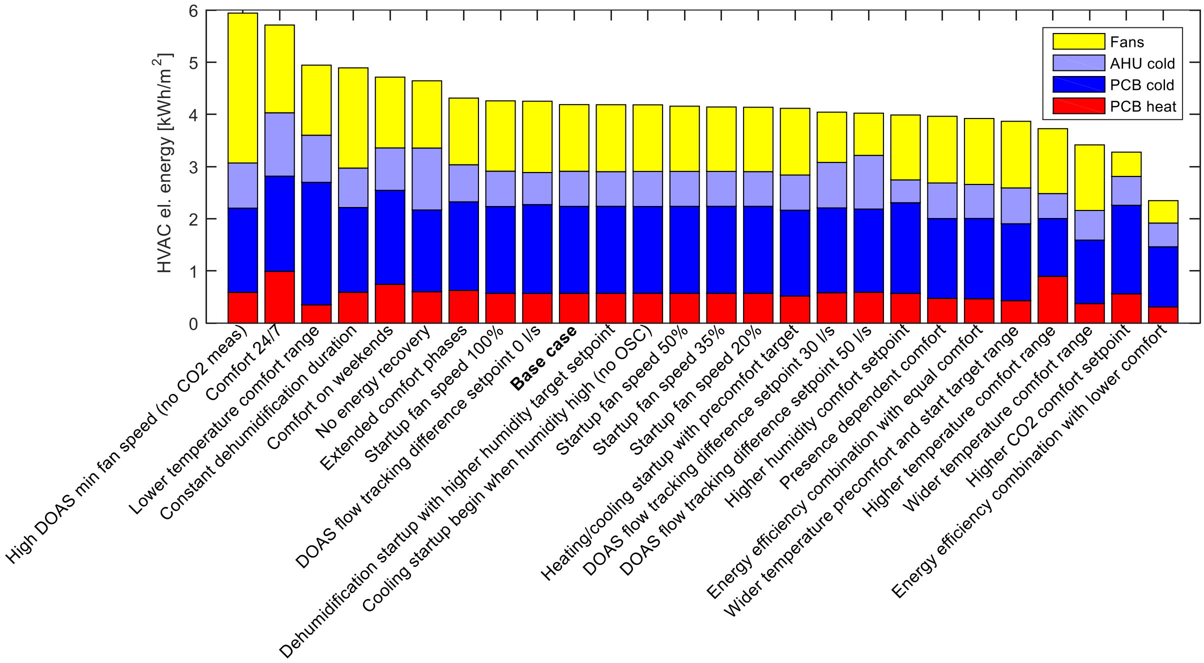

Figure 7: Case study results for (and sorted by) HVAC electrical energy consumption, location New Orleans

Table 2: Simulation results energy consumption in [kWh/m2]

	Singapore				New Orleans				
Nr	**PCB cold**	**AHU cold**	**Fans**	**Total**	**PCB heat**	**PCB cold**	**AHU cold**	**Fans**	**Total**
1	5.1	2.5	1.7	**9.4**	0.6	1.7	0.7	1.3	**4.2**
2	5.3	2.7	1.7	**9.7**	0.6	1.7	0.7	1.3	**4.3**
3	5.6	3.1	1.9	**10.7**	0.7	1.8	0.8	1.4	**4.7**
4	6.0	4.5	1.7	**12.1**	1.0	1.8	1.2	1.7	**5.7**
5	4.5	2.4	1.7	**8.5**	0.4	1.2	0.6	1.3	**3.4**
6	5.2	2.1	1.0	**8.3**	0.6	1.7	0.6	0.5	**3.3**
7	5.2	2.2	1.6	**9.0**	0.6	1.7	0.4	1.2	**4.0**
8	4.2	2.2	1.6	**8.0**	0.9	1.1	0.5	1.2	**3.7**
9	6.1	2.9	2.0	**11.0**	0.4	2.3	0.9	1.3	**4.9**
10	4.8	2.6	1.8	**9.2**	0.5	1.5	0.7	1.3	**4.0**
11	4.6	2.6	1.8	**9.0**	0.4	1.5	0.7	1.3	**3.9**
12	5.1	2.6	2.5	**10.2**	0.6	1.7	0.7	1.3	**4.3**
13	5.2	2.5	1.5	**9.1**	0.6	1.7	0.7	1.2	**4.2**
14	5.2	2.4	1.3	**8.9**	0.6	1.7	0.7	1.2	**4.1**
15	5.2	2.4	1.3	**8.9**	0.6	1.7	0.7	1.2	**4.1**
16	5.0	2.6	1.8	**9.4**	0.5	1.6	0.7	1.3	**4.1**
17	5.1	2.5	1.8	**9.5**	0.6	1.7	0.7	1.3	**4.2**
18	5.1	2.5	1.7	**9.4**	0.6	1.7	0.7	1.3	**4.2**
19	5.1	2.7	2.0	**9.8**	0.6	1.6	0.8	1.9	**4.9**
20	5.2	2.3	1.8	**9.4**	0.6	1.7	0.6	1.4	**4.3**
21	5.0	3.5	1.4	**9.9**	0.6	1.6	0.9	1.0	**4.0**
22	4.9	4.3	1.2	**10.4**	0.6	1.6	1.0	0.8	**4.0**
23	4.8	2.5	1.6	**8.9**	0.5	1.5	0.7	1.3	**3.9**
24	4.3	1.9	0.7	**7.0**	0.3	1.2	0.5	0.4	**2.3**
25	5.0	3.2	3.4	**11.6**	0.6	1.6	0.9	2.9	**5.9**
26	4.8	5.0	1.9	**11.7**	0.6	1.6	1.2	1.3	**4.6**
27	0.0	10.1	2.9	**13.0**	n.a.	n.a.	n.a.	n.a.	n.a.

Results for start-up settings cases (12-19) show fewer differences than for the Singapore location because cooling/dehumidification demand during start-up is much lower (for the simulated time period). Still, reduced start-up fan speeds lower HVAC electrical energy consumption. Flow tracking cases (20-22) results deviate from the Singapore cases: higher flow tracking set points lower total HVAC electrical energy consumption. Cold energy still increases with higher set points, but the lower fan energy consumption does lead to an overall lower consumption.

3.3 Automatic Optimization of Start-up Settings

Instead of manually specifying start-up settings (in particular fan speeds), an automatic optimization can be implemented, provided the necessary measurements are available. For the 3for2 system, such an optimization was tried out using data-driven models for the dehumidification performance of the ventilation system, for the fan curves as well as for the humidity load by outside air infiltration. These three models are then used to determine the optimal fan speed at every point in time within the start-up while the duration of the start-up phase is still learned by a classical OSC function.

CONCLUSIONS

Low-exergy building cooling and ventilation systems are uncommon but promising for applications in hot and humid climates. The paper presents a small-scale simulation case study of such a system using a model of the 3for2 system installed at UWCSEA in Singapore. The authors would like to underscore the importance and practical relevance of the results presented in this paper for the following reasons: (i) the model was calibrated with data collected by the Building Management System (BMS) of the very well instrumented demonstrator building, and (ii) the control functionalities used in the simulations are identical to the ones in the commercial building automation system that was implemented in the demonstrator building.

The results show that demand controlled ventilation (despite relatively low volumetric flow needed by the 3for2 system) based on CO_2 concentration, absolute humidity and presence detection are important factors which contribute favorably towards the overall energy efficiency of the system. For the Singapore location, demand controlled ventilation based on CO_2 concentration and based on presence detection leads to a 23% and 4.4% reduction, respectively, in total HVAC electrical energy consumption. The results strongly justify the installation of the CO_2 sensors and presence detectors. Further advantages of such installations are less noise and maintenance costs due to lower fan speeds, and increased comfort energy efficiency when combined with automatic light control.

For similar installation and comparable comfort, the control settings account for a difference of around 10% in total HVAC electrical energy use within the investigated cases. More specifically, the results show that start-up and flow-tracking control settings have a significant impact on energy use. Low airflow settings during start-up may extend the start-up duration, but allow for significant savings in fan energy. Start-up operation can be optimized automatically by data-driven model based calculations if the required measurements are available. Unbalanced DOAS fresh air and exhaust air flow lowers the heat recovery potential which can lead to additional total HVAC electrical energy use of more than 10% for the Singapore cases. This shows the importance of a closed-loop controlled flow tracking which compensates for unbalanced flow due to under-maintained air filters or closed dampers. Most control related results can be transferred to central cooling and ventilation systems as well as conventional air-based only HVAC systems for which in particular the start-up optimization is promising.

The investigated control strategies still have room for energy efficiency improvement, mainly by further reducing operation whenever there is no occupancy. Such a strategy is studied in (Peng, 2018) and can be combined with the strategies described in this paper. Furthermore, control strategies that adapt the operation to individual comfort requirements ideally lead to higher productivity of the building users, but might also lower energy efficiency. Again, such strategies can complement the presented strategies.

4 ACKNOWLEDGEMENTS

This work was undertaken as part of the project 3for2 Beyond Efficiency. The support and founding by United World College South East Asia (UWCSEA) and Siemens Building Technologies is gratefully acknowledged.

5 REFERENCES

Apte, M. G. (2006). *A Review of Demand Control Ventilation*. Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings, vol. 4 p. 371-376.

Gao, T. et al. (2007). *Multizone building with VAV air-conditioning system simulation for evaluation and test of control systems.* Building Simulation 2007. Beijing, China.

Garcia-Sanz, M. et al. (1994). *Adaptive optimum start-up and shut-down time controllers for heating systems based on a robust gradient method*. Control Theory and Applications, IEE Proceedings, vol.141, p.323 – 328.

Pantelic, J. et al. (2017). *Comparing the indoor environmental quality of a displacement ventilation and passive chilled beam application to conventional air-conditioning in the Tropics.* Building and Environment 130 (2018) 128-142.

Peng, Y. et al. (2018). *Using machine learning techniques for occupancy-prediction-based cooling control in office buildings.* Applied Energy 211 (2018) 1343-1358.

Rysanek, A. et al. (2015a). *The design of a decentralized ventilation system for an office in Singapore: key findings for future research*. CISBAT 2015 International Conference on Future Buildings and Districts. Lausanne, Switzerland.

Rysanek, A. et al. (2015b). *Simulation analysis of a low-exergy decentralized air-conditioning system for hot and humid climates.* In 14th International Conference of the International Building Performance Simulation Association (IBPSA). Building Simulation 2015. Hyderabad, India: IBPSA.

Schlueter, A. et al. (2016). *3for2: Realizing Spatial, Material, and Energy Savings through Integrated Design*. CTBUH Journal 2016(2):40-45.

Seshadri, B. et al. (2017). *Evaluation of low-lift sensible cooling in the tropics using calibrated simulation models and preliminary testing*. CISBAT 2017 International Conference on Future Buildings and Districts. Lausanne, Switzerland.

TRNSYS 17 (2014). *TESSLibs 17 documentation - component libraries for the TRNSYS simulation environment.* Thermal Energy System Specialists, LLC of Madison, Wisconsin, USA.