Generalized heuristic control for direct expansion (DX) cooling systems with capacity modulation and variable air flow

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2014 Purdue Conferences
Compressor Engineering
Refrigeration and Air Conditioning
High Performance Buildings

Outline

- Introduction
- Component models
- Fan-duct systems
- Optimal operations
- Control heuristics
- Energy saving assessment with simulation

Introduction

Motivation:

- Direct expansion (DX) air conditioning systems are widely used in small- to medium-sized commercial buildings
- More DX units are equipped with variable speed drives (VSD) since VSD becomes more affordable
- Need an implementable and model-free control strategy

Approach:

- DX units with different types of compressors are modeled from catalog data
- Different fan-duct system characteristics are considered
- Optimization is performed to the integrated system model
- Obtain a generalized control heuristics from the optimal results

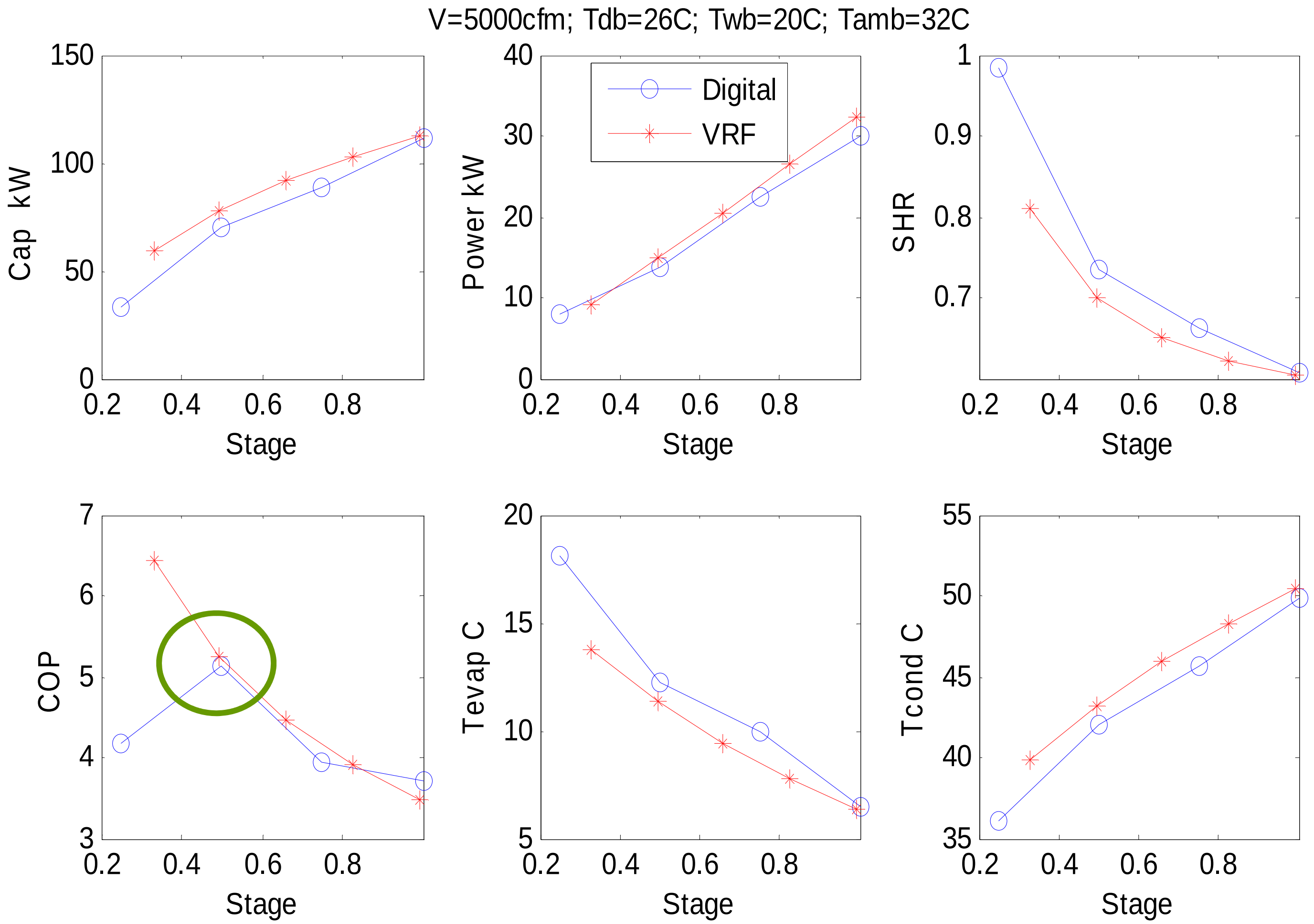
DX models

Component-model descriptions:	Input-output forms :
Compressor • Empirical catalog model	$\left[P_{comp}, m_r\right] = Compressor\left(\underline{\underline{T_{evap}}}, \underline{\underline{T_{cond}}}, \underline{Stage}\right)$
Condenser & evaporator • Effectiveness-NTU method • Correlate heat transfer coefficients to air and refrigerant mass flow rates	$\left[q_{tot}, q_{sen}\right] = Evap\left(\underline{\underline{T_{evap}}}, \underline{V}, \underline{T_{air,db,evap}}, \underline{T_{air,wb,evap}}\right)$ $q_{cond} = Cond\left(\underline{\underline{T_{cond}}}, \underline{T_{amb}}, m_r\right)$ $\underline{X}$: external inputs (boundary condition). $\underline{\underline{X}}$: internal variables that need to be solved iteratively

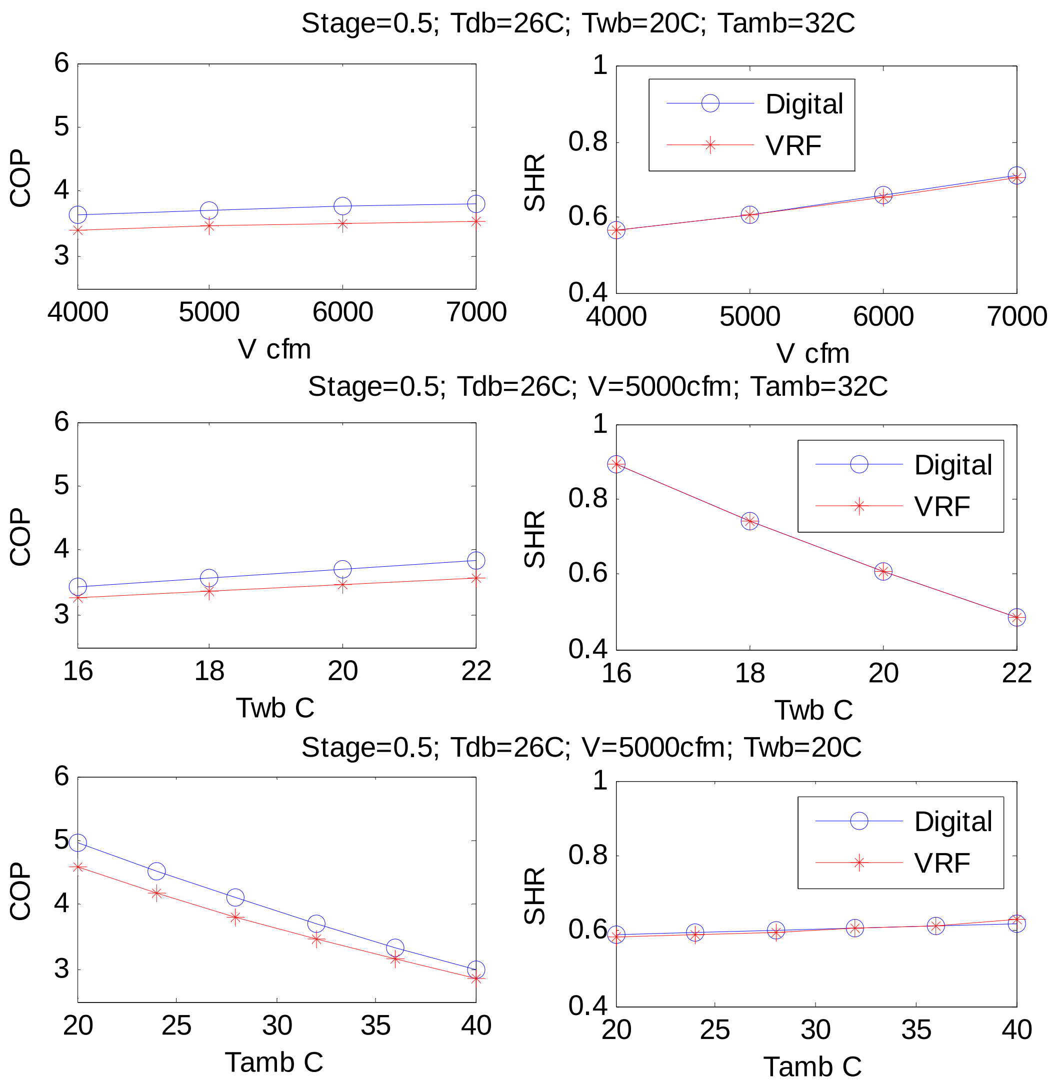
Model integration: Solve $\begin{cases} q_{tot} + 0.95 \times P_{comp} = q_{cond} \\ T_{sc} = 15 \text{ F} \end{cases}$ for $\begin{bmatrix} T_{evap} \\ T_{cond} \end{bmatrix}$

Input-output form: $\left[P_{comp}, q_{tot}, SHR, T_{sup}\right] = DX\left(T_{air,db,evap}, T_{air,wb,evap}, T_{amb}, V, Stage\right)$

Integrated model



Integrated model

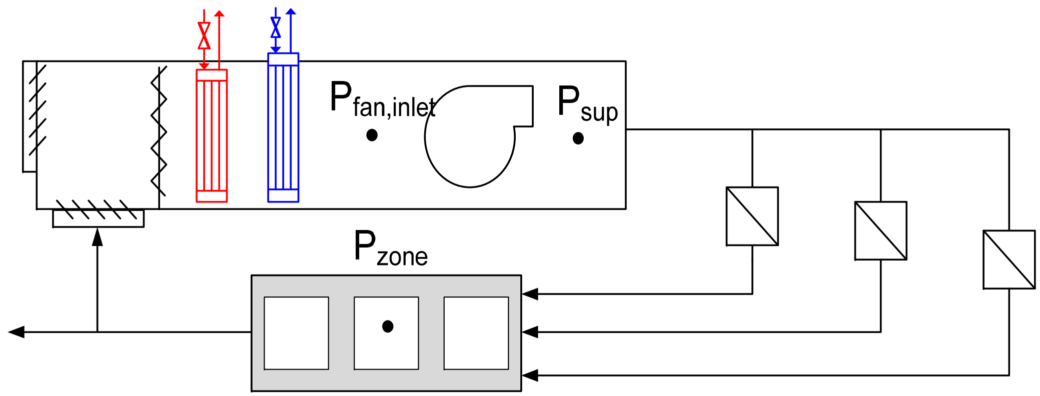


Duct system characteristics

$$ESP = \Delta P_{fan,downstream} + \Delta P_{fan,upstream}$$

$$\Delta P_{fan,downstream} = P_{sup} - P_{zone} = A \cdot V^2$$

$$\Delta P_{fan,upstream} = P_{zone} - P_{fan,inlet} = B \cdot V^2$$



Constant static pressure

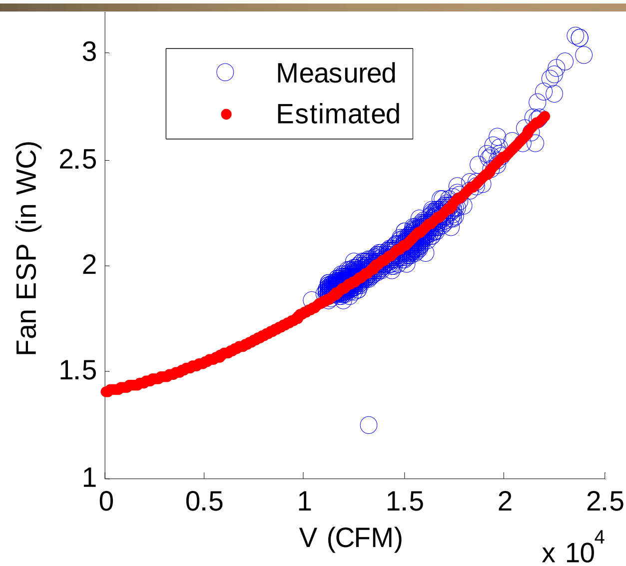
$$ESP = \Delta P_{fan,downstream} + \Delta P_{fan,upstream} = D + B \cdot V^2$$

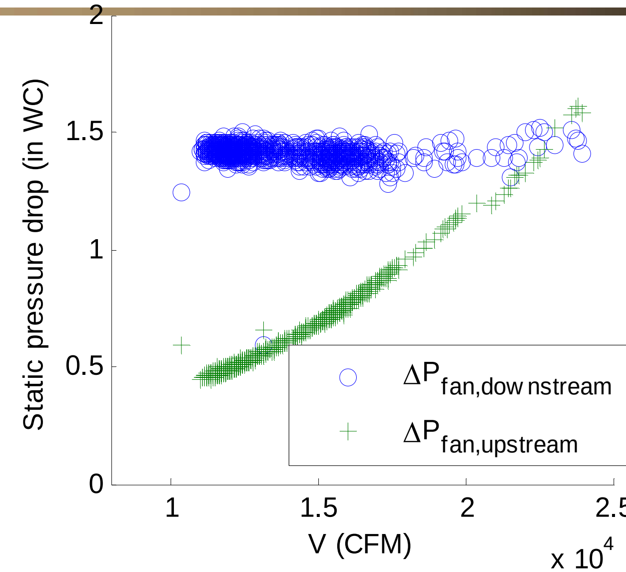
Resetting static pressure

$$ESP = \Delta P_{fan,downstream} + \Delta P_{fan,upstream} = (A + B)V^2 = C \cdot V^2$$

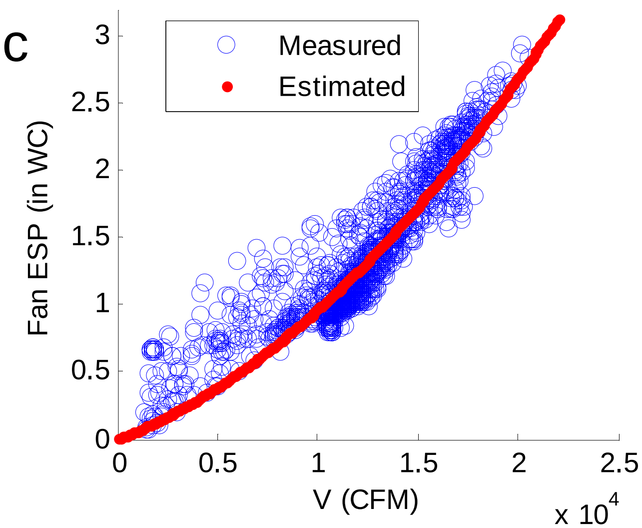
Fan-duct systems

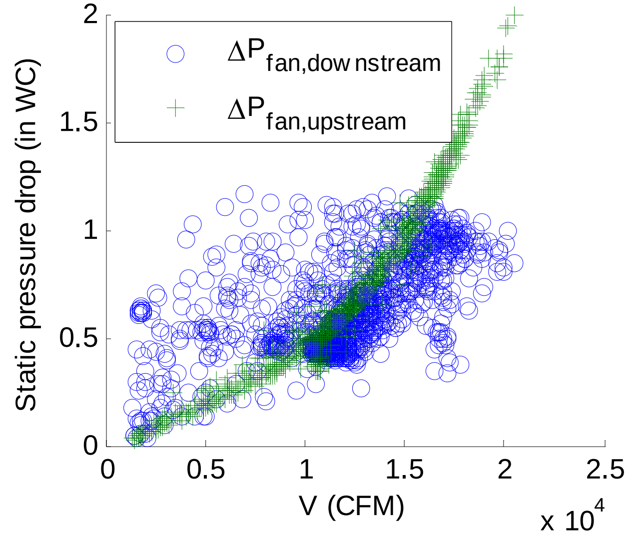
Constant static pressure





Resetting static pressure

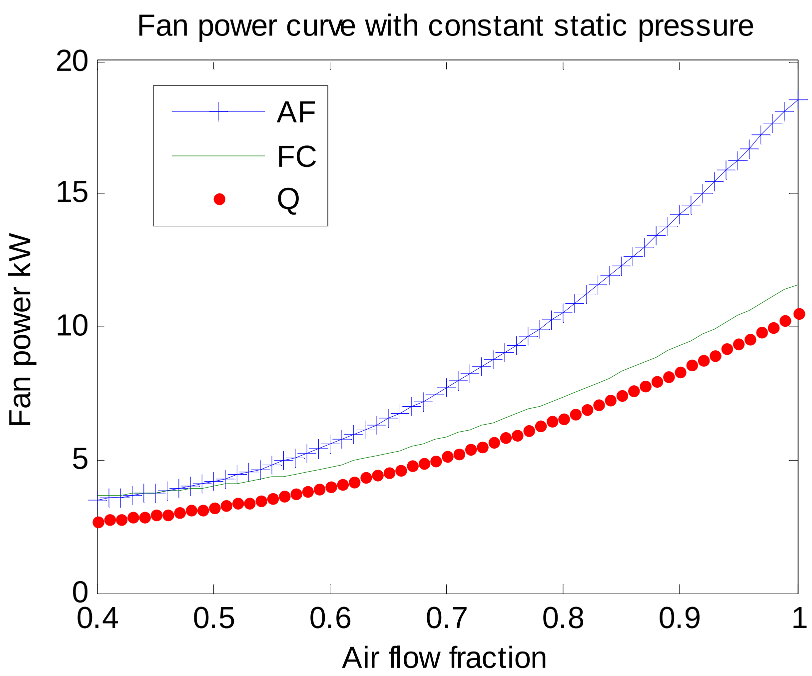


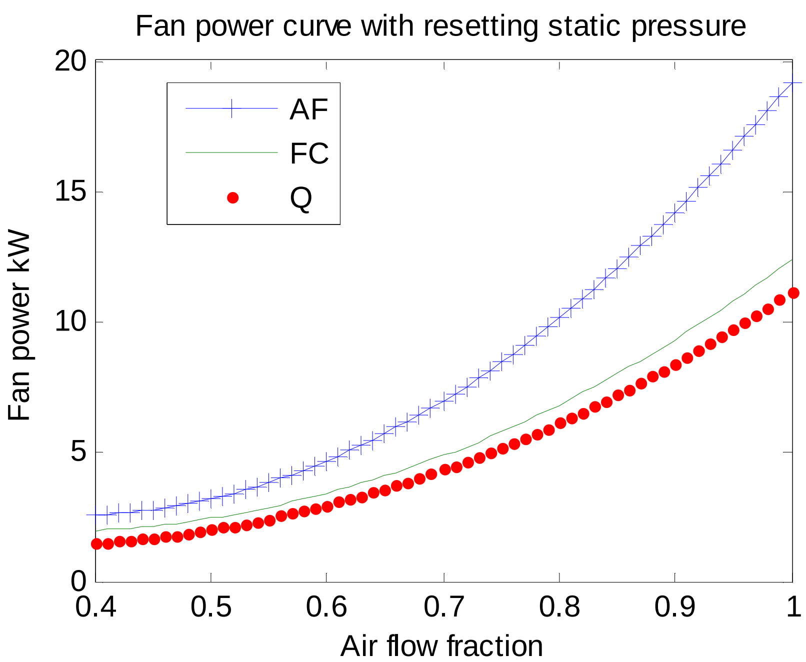


Fans

Three types of fans are considered:

	Diameter (in)	Maximum SP (inwc)	Maximum HP (bhp)
FC (forward curved)	25	5	30
AF (airfoil)	22	8	40
Q (vaneaxial)	36.5	5	30





Optimization problem formulation

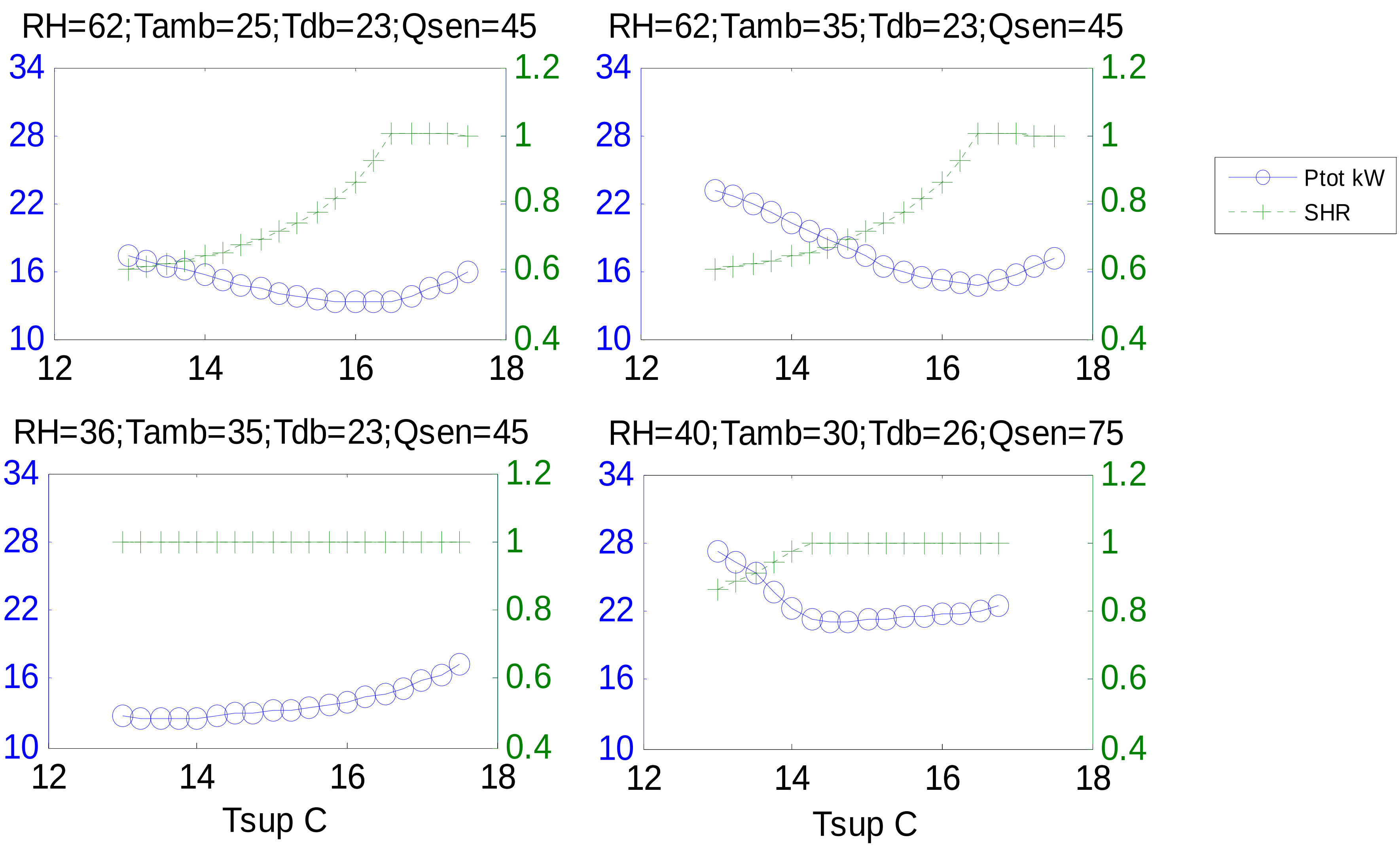
Problem formulation:

$$T_{sup,opti} = \arg\min_{T_{sup}} P_{DX}\left(\overline{T_{air,db,evap}, T_{air,wb,evap}, T_{amb}}, V, T_{sup}\right) + P_{fan}(V)$$

$$\text{satisfying}\begin{cases} q_{sen} = \overline{q_{sen,req}} \\ SHR < \overline{SHR_{\max}} \\ V_{\min} < \dot{V} < V_{\max} \\ Stage \in [0,1] \\ T_{\min} < T_{sup} < T_{\max} \end{cases}$$

- SHR_{max} -- dehumidification lower limit
- Overbar variable -- boundary condition or requirements

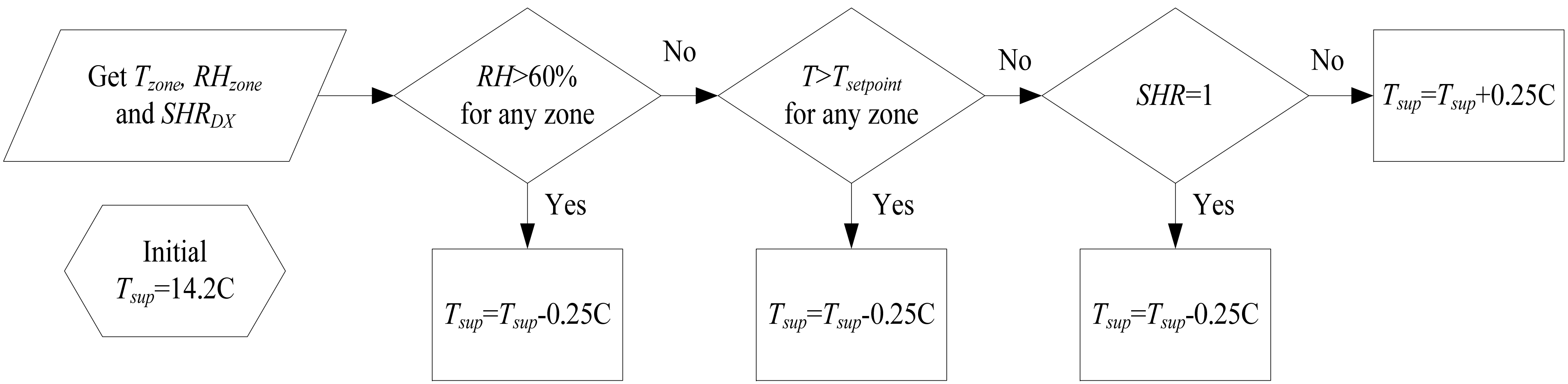
Visualization of optimization results



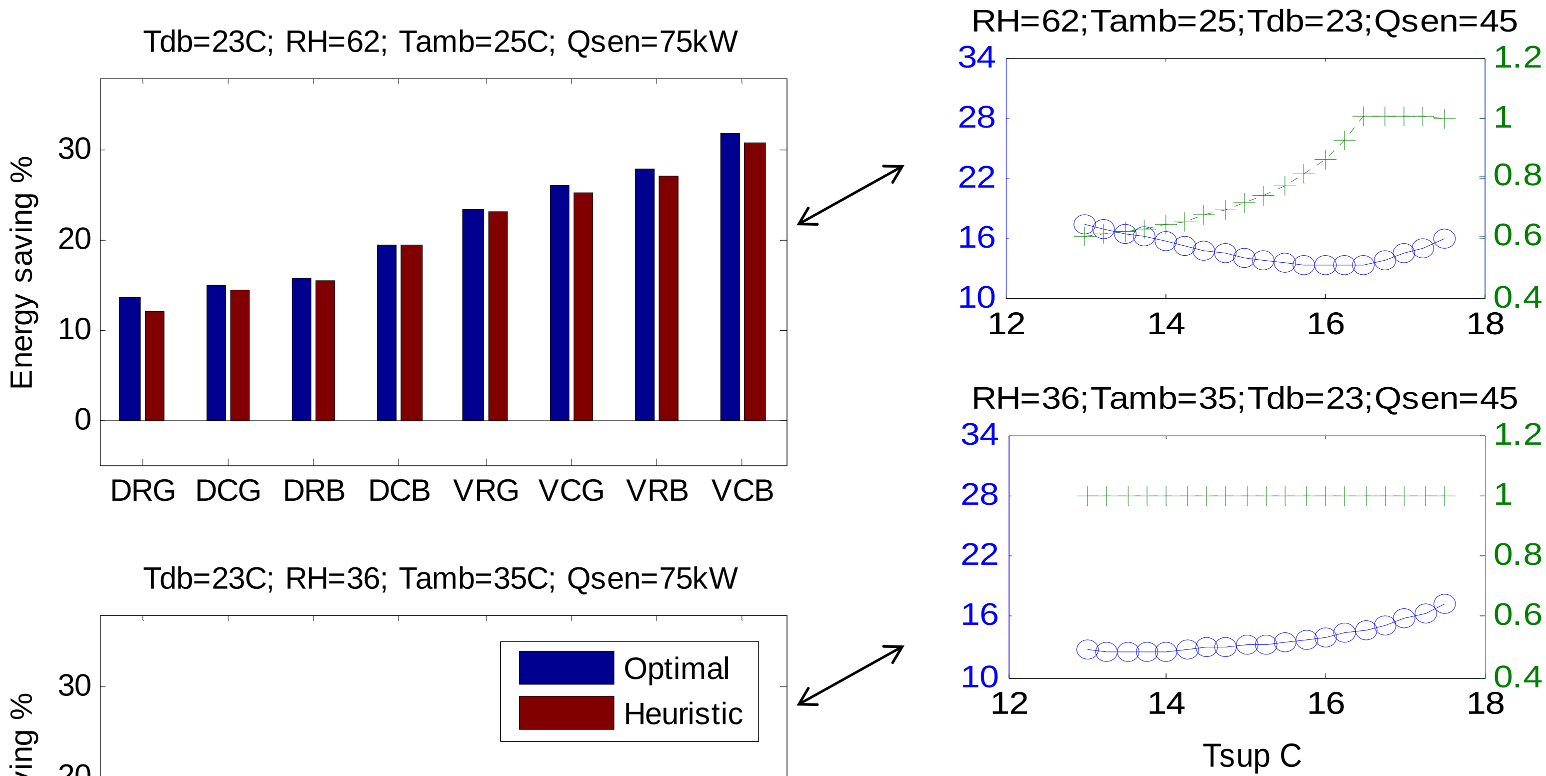
Control heuristics

Control heuristics:

Increase the supply air temperature setpoint until the SHR upper bound is reached

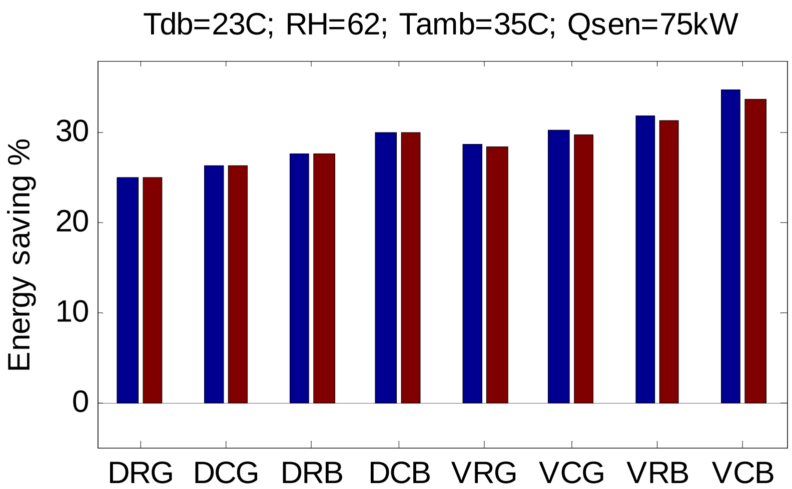


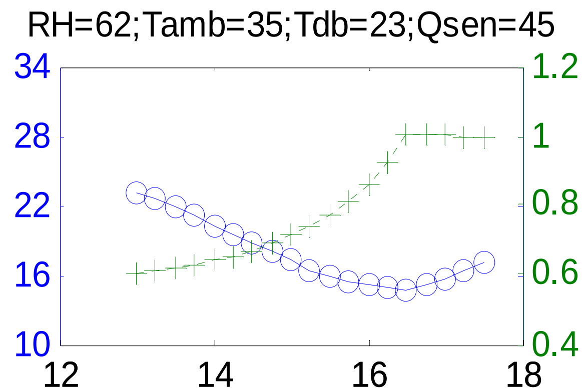
Compare heuristic & optimal control

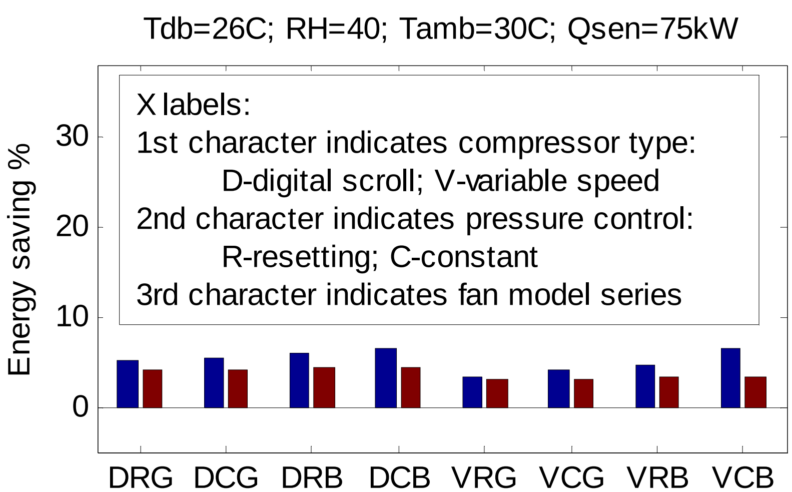


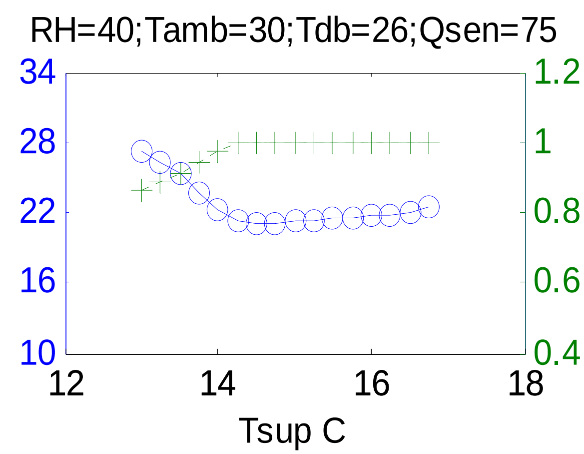
X labels:
1st character indicates compressor type:
D-digital scroll; V-variable speed
2nd character indicates pressure control:
R-resetting; C-constant
3rd character indicates fan model series

Compare heuristic & optimal control





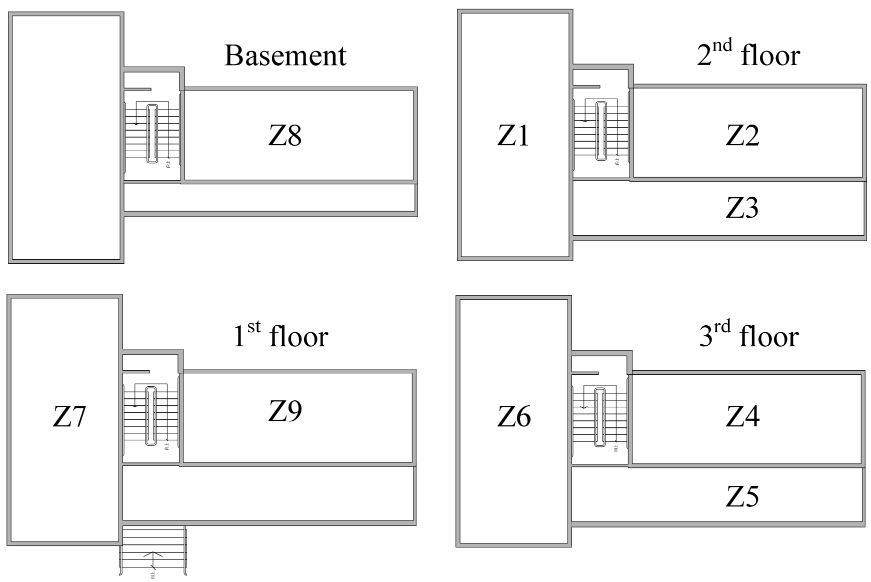


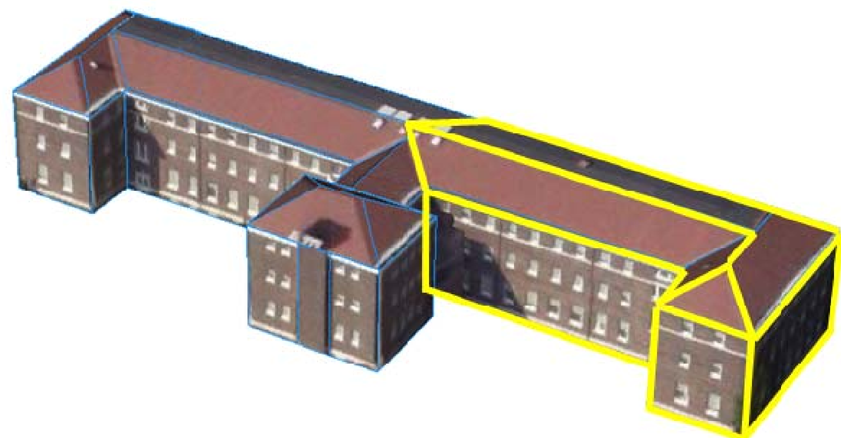


Energy saving assessment-- simulation

Simulation model description:

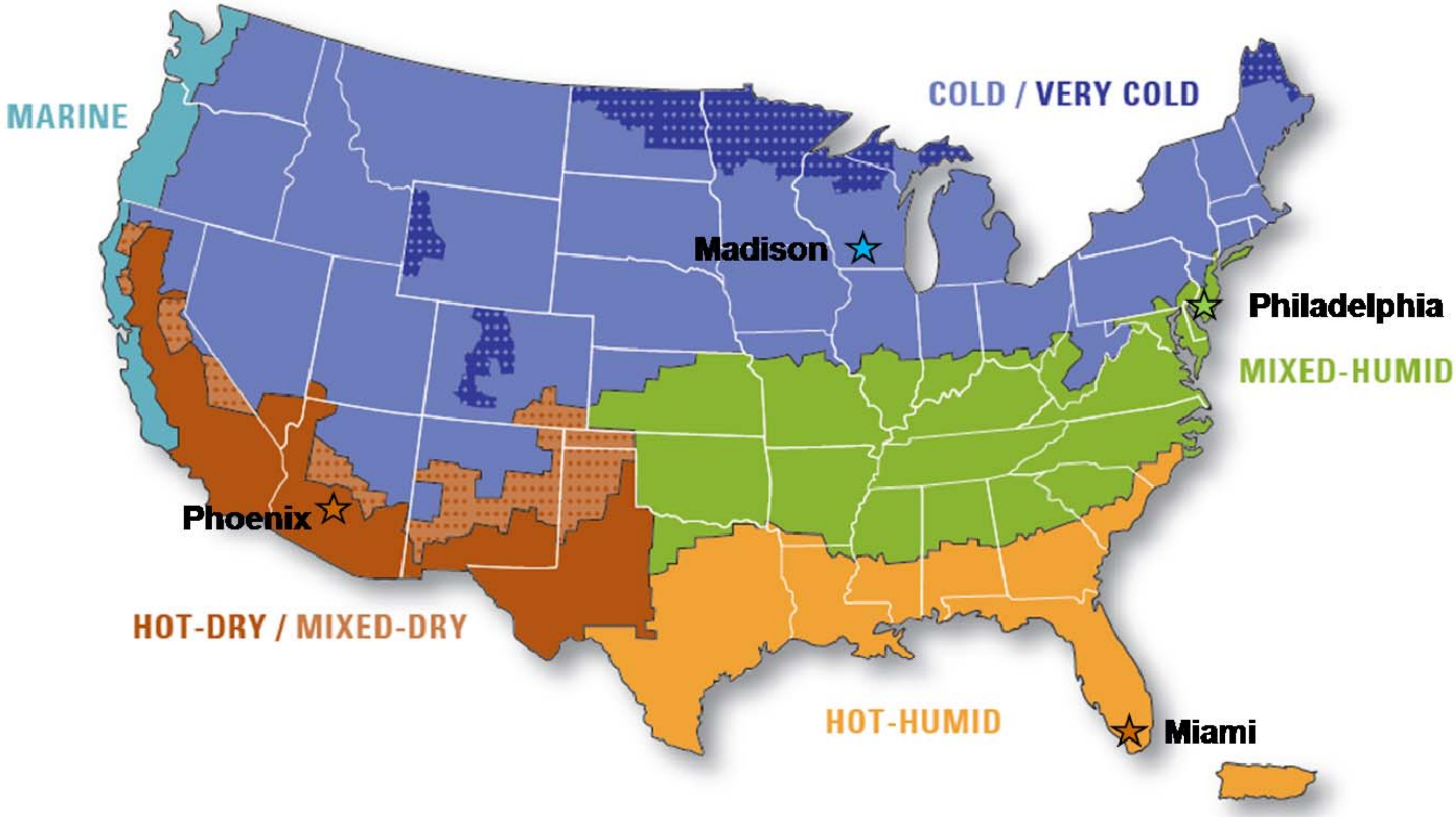
- 9 zone building with total area of 20,000 sq. ft.
- Data driven envelope model
- Night setup strategy and assume perfect setpoint tracking
- Simulate for a 100-day cooling season with TMY2 data



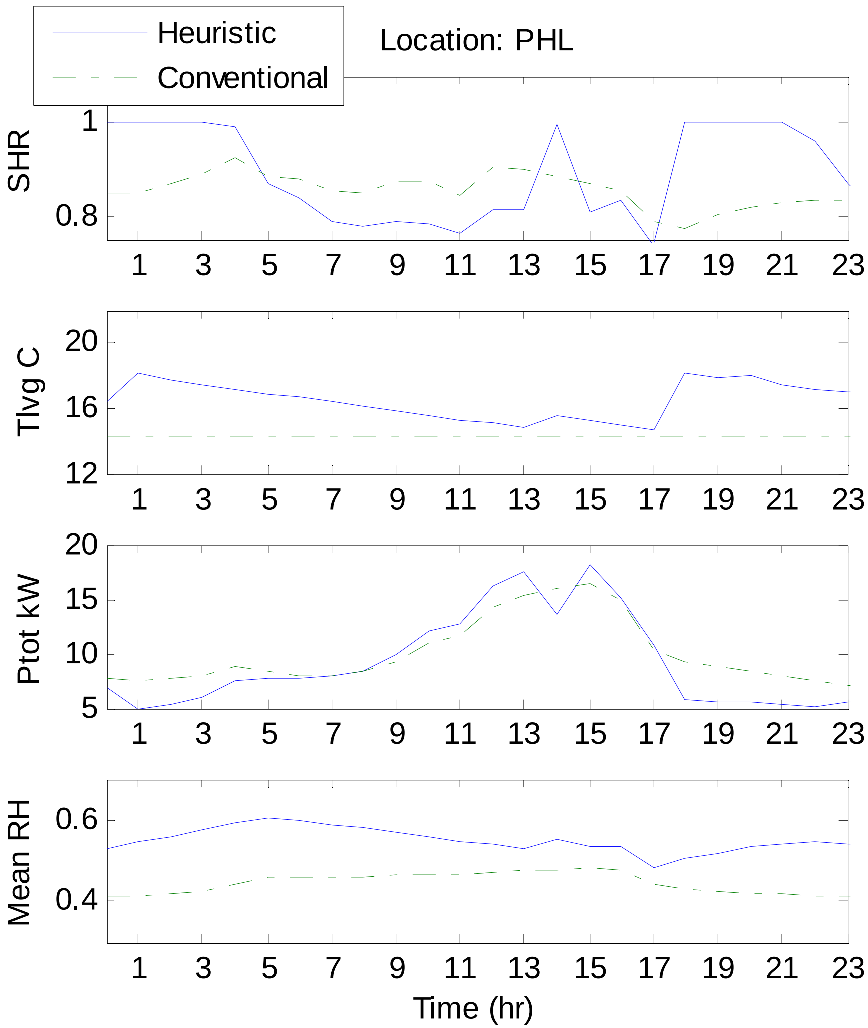


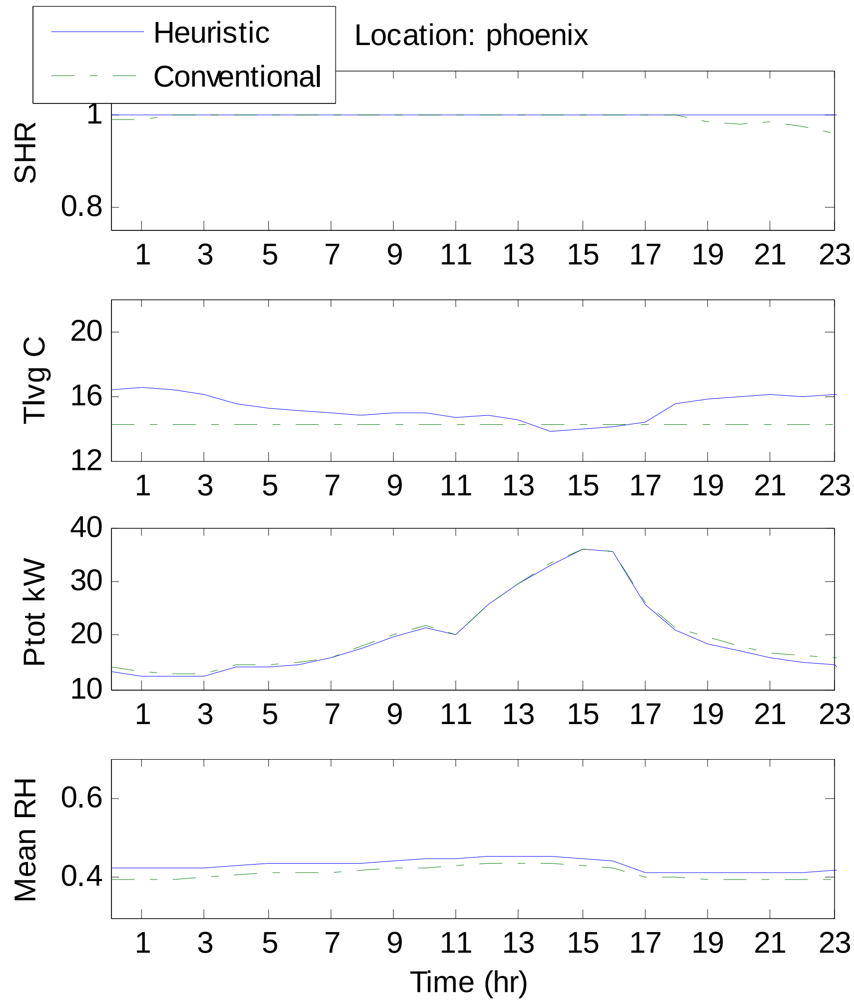
Climate zones for simulation

- Four cities are chosen to represent different climates
- DX unit is scaled according to the peak load



Simulation results





Simulation results

Simulation results:

	Qsen on DX coil (MWh)		Qlatent on DX coil (MWh)		Energy consumption (MWh)			Mean zone RH %	
	Heur.	Conv.	Heur.	Conv.	Heur.	Conv.	Saving	Heur.	Conv.
Philadelphia	130.1	130.4	15	17.5	25.8	27.5	8.5 %	53	45
Miami	143	142.6	31.1	31.4	35.5	36.5	2.9%	57	53
Phoenix	173.1	172.7	7.75	11.9	46.5	48.8	4.8%	52	47
Madison	120.5	122.1	8.3	10.5	22.5	24.8	9.3%	55	48

* Comfort improves in addition to energy savings (not listed in the table)

Conclusion

- Variable speed compressor provides better part-load performance than digital scroll compressor in a DX unit
- For both types of compressor, peak efficiency occurs when the coil condition changes from wet to dry
- *Control heuristics*: increase T_{sup} until a SHR upper bound is reached
- The proposed heuristics provide near-optimal control at any operating condition
- Heuristics leads to more energy savings for systems equipped with variable speed compressor and under constant pressure control
- Significant energy savings can be achieved for a whole cooling season, but is highly dependent on the climate

Thank you!

Q&A