Thermal Comfort as Related to Energy Consumption: What is the Balance?

DR. TOM LAWRENCE, PE, LEED-AP, F-ASHRAE

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Course Description

Maintaining thermal comfort within an occupied building requires energy, thus optimized solution methods for balancing energy use with indoor environmental quality are needed. Demand response programs commonly include temporary adjustments to space temperature set points and thus can affect the occupants' thermal comfort perceptions. Current building temperature control systems often do not take into account the adaptive capability of the occupants, but this concept can be used advantageously during implementation of demand response. How to balance the overall energy consumption and peak demand for cooling or heating within buildings with the need for maintaining adequate thermal comfort in the built environment is an issue important to system designers, building operators and society as a whole. This session provides an overview of the historical development of thermal comfort perception, and how these are incorporated in ASHRAE Standard 55. Also covered is addressing the conflicting balance between energy consumption and thermal comfort, and a vision on how to possibly achieve an overall optimized balance.

Learning Objectives

Recognize the basis for how the human body regulates temperature and factors contributing to thermal comfort perception.

Be able to describe evolution of the historical development of thermal comfort perception and ASHRAE Standard 55.

Understand the concept of adaptive capability of people with regard to the thermal environment.

Recognize how temporary HVAC measures for demand response could influence occupant thermal comfort.

Identify the potential for an overall optimized balance of occupant thermal comfort and energy demand.

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Topics Covered

What factors are involved with human thermal comfort and comfort perception

The evolution of understanding thermal comfort

Thermal comfort in codes and standards

How HVAC systems might participate in electrical demand response measures

Finding the Balance of Maintaining Thermal Comfort and Energy Demand, Consumption

Human Thermal Regulation and Comfort Perception

Purpose of ventilation and conditioned environment

Provide a healthy environment to the occupants to sustain life

Provide a comfortable environment that allows the occupants to perform at their best

Factors influencing comfort perception

- **Temperature**
- **Humidity**
- **Airflow velocity**
- **Thermal radiation**
- **Air quality**
- **Noise**
- **Light levels**
- **Recent temperature exposure**
- **Age**
- **Gender**
- **"Mood"**
- **Time of exposure**
- **Adaptive mechanisms**
- **Type of activity**
- **Building type**
- **Local cultural norms**

Transient Thermal Model for Humans

$$(M - W) \pm C \pm R - E = S$$

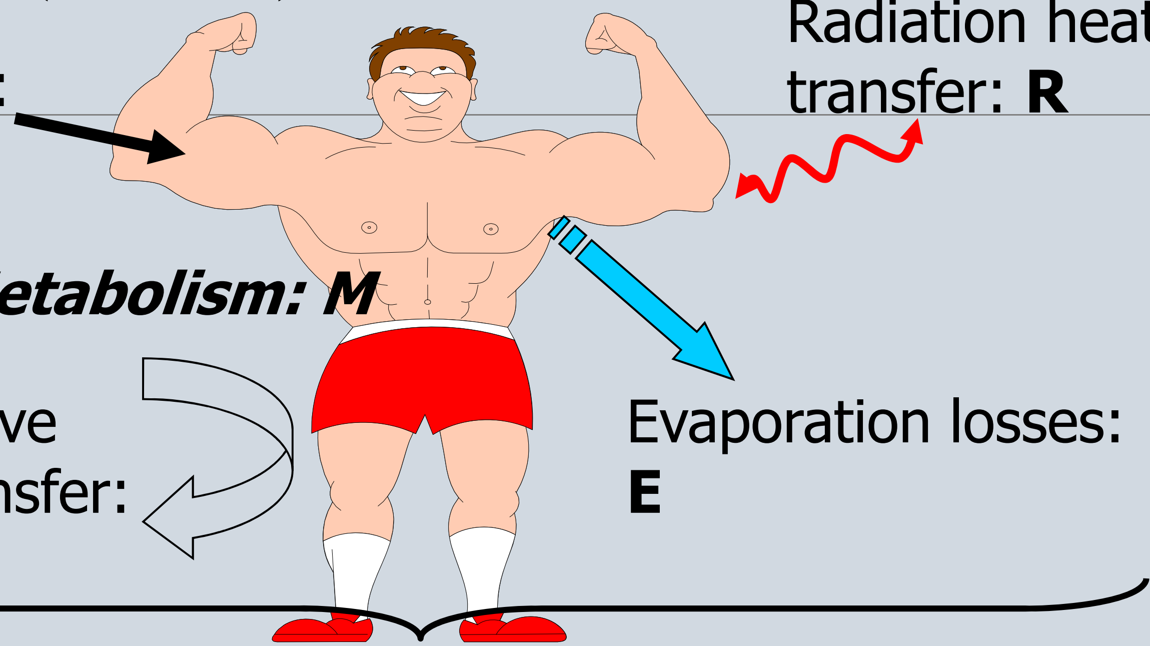
Work expended: **W**

Radiation heat transfer: **R**

Metabolism: M

Convective heat transfer: **C**

Evaporation losses: **E**



Overall change in body heat (storage): S

"The sum of all heat generated minus the work expended and the net thermal exchange with the environment equals the change in body heat content"

If at equilibrium: $(M - W) = \pm C \pm R + E$

Transient Thermal Model for Humans (Cont'd)

Clothing provides insulation effect, but quantifying the net heat transfer coefficient is difficult

One standard measure is the *clo;* 1 clo is amount of insulation necessary to maintain:

- Skin T = 92°F
- In room at 70°F
- Air movement not over 10 ft/min
- Humidity not over 50%
- Metabolic rate of 360 Btu/hr

clo values are additive

Evolution of Thermal Comfort Understanding and Evaluations

What is “Thermal Comfort”?

Very subjective: “the condition of mind which expresses satisfaction with the thermal environment” [Standard 55]

Thermo-physiological definition relates thermal comfort to “the firing of the thermal receptors in skin and in hypothalamus” (Hoppe 2002) Energy and buildings, 34(6), pp.661-665

Others:
“the state that people strive for when they feel discomfort”
or “a recognizable state of feeling”

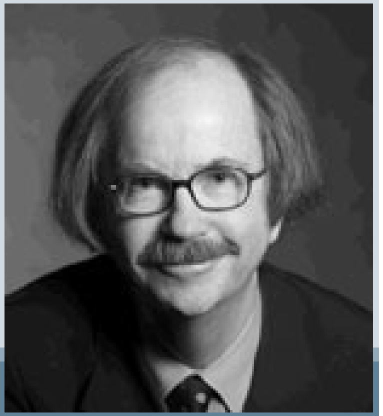
Indices of Thermal Comfort

Effective temperature: Houghten and Yaglou (1925)

- Sensory scale to determine warmth as combination of air temperature, humidity and air velocity into single numerical index
- Widely used for 50 years

Fanger – Heat Balance Model: "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD)

"mean thermal sensation vote for a large group of building occupants for any given combination of thermal environmental variables, activity and clothing levels"



Ole Fanger:
International Centre for Indoor Environment and Energy
Technical University of Denmark

PMV Calculation

$$PMV = [0.303e^{\{-0.036M\}} + 0.028]\{(M - W) - 3.96e^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4]$$

$$-f_{cl}h_{cl}(t_{cl} - t_a) - 3.05[5.73 - 0.007(M - V) - p_a] - 0.42[(M - W) - 58.15]$$

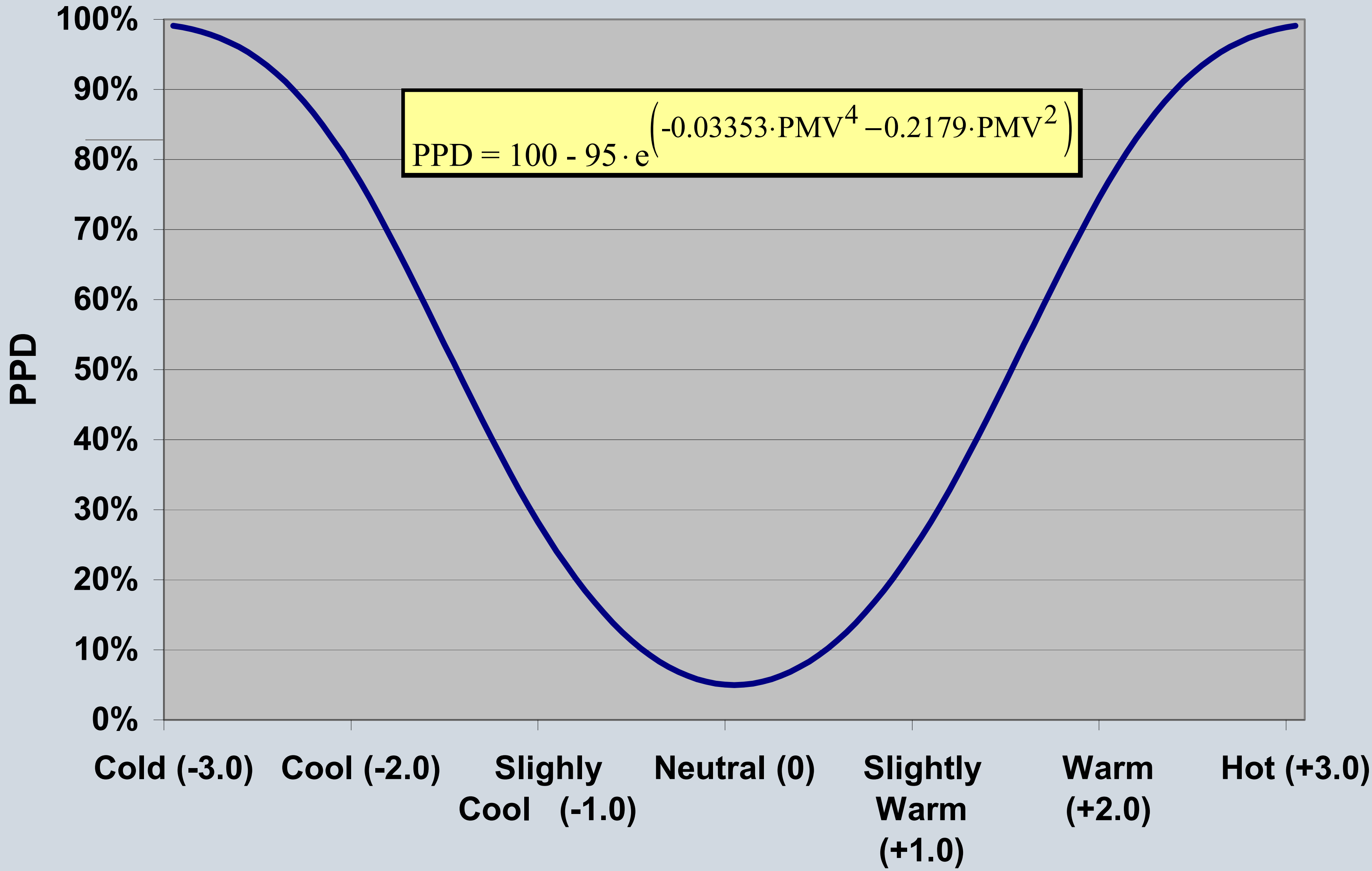
$$-0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\}$$

Where,

$$f_{cl}\begin{cases}1.0 + 0.29I_{cl}, & I_{cl} < 0.078 \quad m^2.C/W \\ 1.05 + 0.645I_{cl}, & I_{cl} \geq 0.078 \quad m^2.°C/W\end{cases}$$

Need a better alternate …

Fanger Comfort Model for PPD



PMV for this Room

PREDICTED MEAN VOTE ESTIMATOR		
"COMFORT"	**#Votes**	**Score**
Cold	0	0
Cool	0	0
Slightly Cool	14	-14
Neutral	15	0
Slightly Warm	4	4
Warm	0	0
Hot	0	0
Total	33	-10
	PMV=	**-0.30303**
	PPD =	**6.9%**

Issues with the Heat Balance Model, PMV-PPD

- Much of the testing for judging thermal comfort reactions has been done in laboratory settings of college-age students in steady-state conditions; with subjects knowing they were part of the testing.
- Assuming the population in question would actually consider comfort with 'neutral' PMV (=0)
- Different expectations
- Humphreys and Nicol (2002) stated that PMV is only valid between -0.5 and +0.5 and the bias grows larger as it goes away from the neutral condition

Don’t Get Me Wrong…

- Using the tools and charts described up to know are good resources for design and operation (at least rules of thumb)
- But, how can we improve on this thinking?

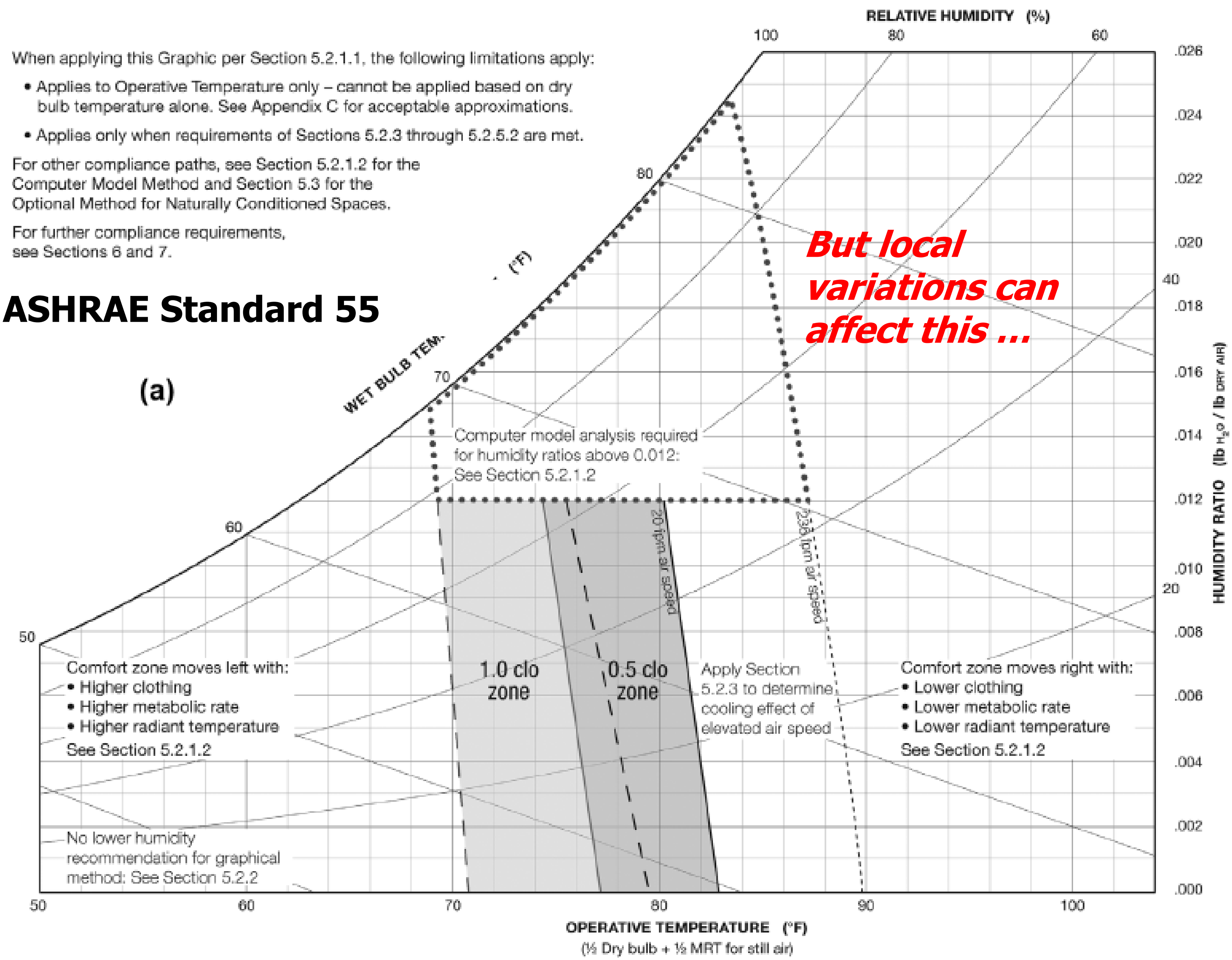
Adaptive Comfort Concept

Adaptation:

- "gradual diminution of organism's response to repeated environmental stimulations and subsumes all processes which building occupants undergo in order to improve the 'fit' of the indoor climate to their personal or collective requirements"
- Thomas Bedford, 1936 – Adaptive Thermal Comfort Model

Thermal Comfort in Codes and Standards

ASHRAE Standard 55



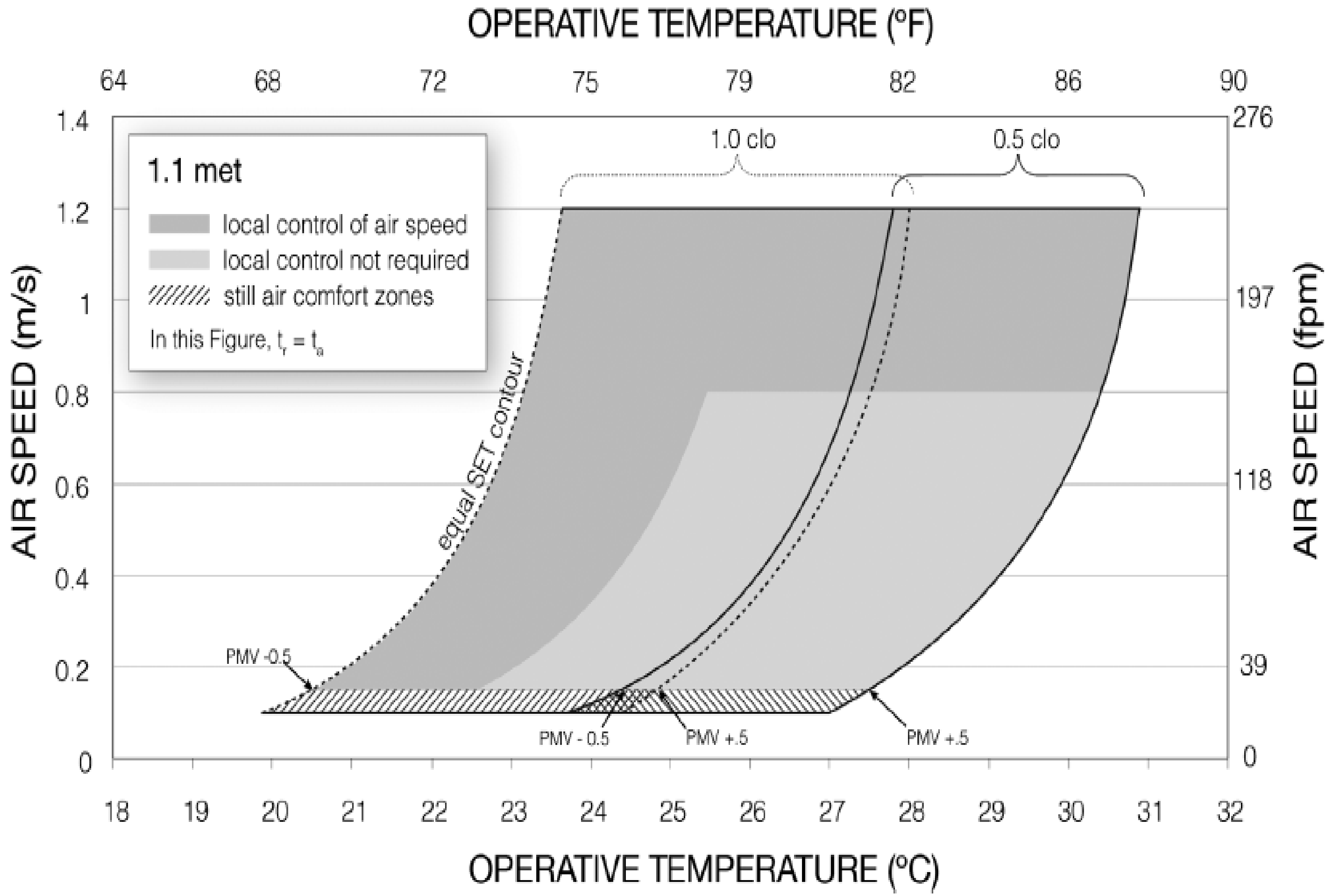


Figure 5.2.3.2 Acceptable range of operative temperature and air speeds for the comfort zone shown in Figure 5.2.1.1, at humidity ratio 0.010.

Basis for the Standards

- The Rationale or Heat Balance approach are still core to ASHRAE Standard 55 and ISO 7730
- Adaptive approach is allowed in Standard 55, but only for naturally ventilated buildings

HVAC System Implementation of Demand Response Measures

LEED v4 EA Credit: Demand Response

Building project can opt to pursue the following credit options

Case 1: Demand Response Program Available (2 pts)

- Participate in the program through contract
- Design system with capability for automate DR (Semi-automated allowed in practice)
- Include DR in the commissioning

Case 2: DR Program NOT Available (1 pt)

- Provide infrastructure to take advantage of a future DR program, including meters and developing a comprehensive plan for load shedding of at least 10%

Demand Response is Becoming “Code”

- ASHRAE Standard 189.1: includes a limitation on building peak electrical demand
- International Green Construction Code: When required by the local building code authority:
  - Automated demand response infrastructure via building energy management system
  - Achieve 10% HVAC reduction through combination of:
    - Space temperature resets or disabling in unoccupied areas
    - Chilled, hot water supply temperature reset
    - Equipment cycling
    - Limiting capacity of supply fans, pumps
    - Anticipatory control strategies (precool, preheat)
  - Include control logic to include “rebound avoidance”

California (Title 24)

SECTION 120.2 – REQUIRED CONTROLS FOR SPACE-CONDITIONING SYSTEMS

(h) **Automatic Demand Shed Controls.** HVAC systems with DDC to the Zone level shall be programmed to allow centralized demand shed for non-critical zones as follows:

1. The controls shall have a capability to remotely setup the operating cooling temperature set points by 4 degrees or more in all non-critical zones on signal from a centralized contact or software point within an Energy Management Control System (EMCS).

2. The controls shall have a capability to remotely setdown the operating heating temperature set points by 4 degrees or more in all non-critical zones on signal from a centralized contact or software point within an EMCS.

3. The controls shall have capabilities to remotely reset the temperatures in all non-critical zones to original operating levels on signal from a centralized contact or software point within an EMCS.

4. The controls shall be programmed to provide an adjustable rate of change for the temperature setup and reset.

5. The controls shall have the following features:

   A. Disabled. Disabled by authorized facility operators; and

   B. Manual control. Manual control by authorized facility operators to allow adjustment of heating and cooling set points globally from a single point in the EMCS; and

   C. Automatic Demand Shed Control. Upon receipt of a demand response signal, the space-conditioning systems shall conduct a centralized demand shed, as specified in Sections 120.2(h)1 and 120.2(h)2, for non-critical zones during the demand response period.

Implementing Demand Response (DR) in Buildings

- What types of actions are possible?
- Planning for a new building versus retrofitting in an old building
- The obvious first choices:
  - HVAC systems
    - Setpoints
    - Thermal energy storage
  - Lighting

Perhaps you have considered:
- Plug load management
- General overall energy conservation effects

Other more unique considerations
- Non-traditional thermal energy storage

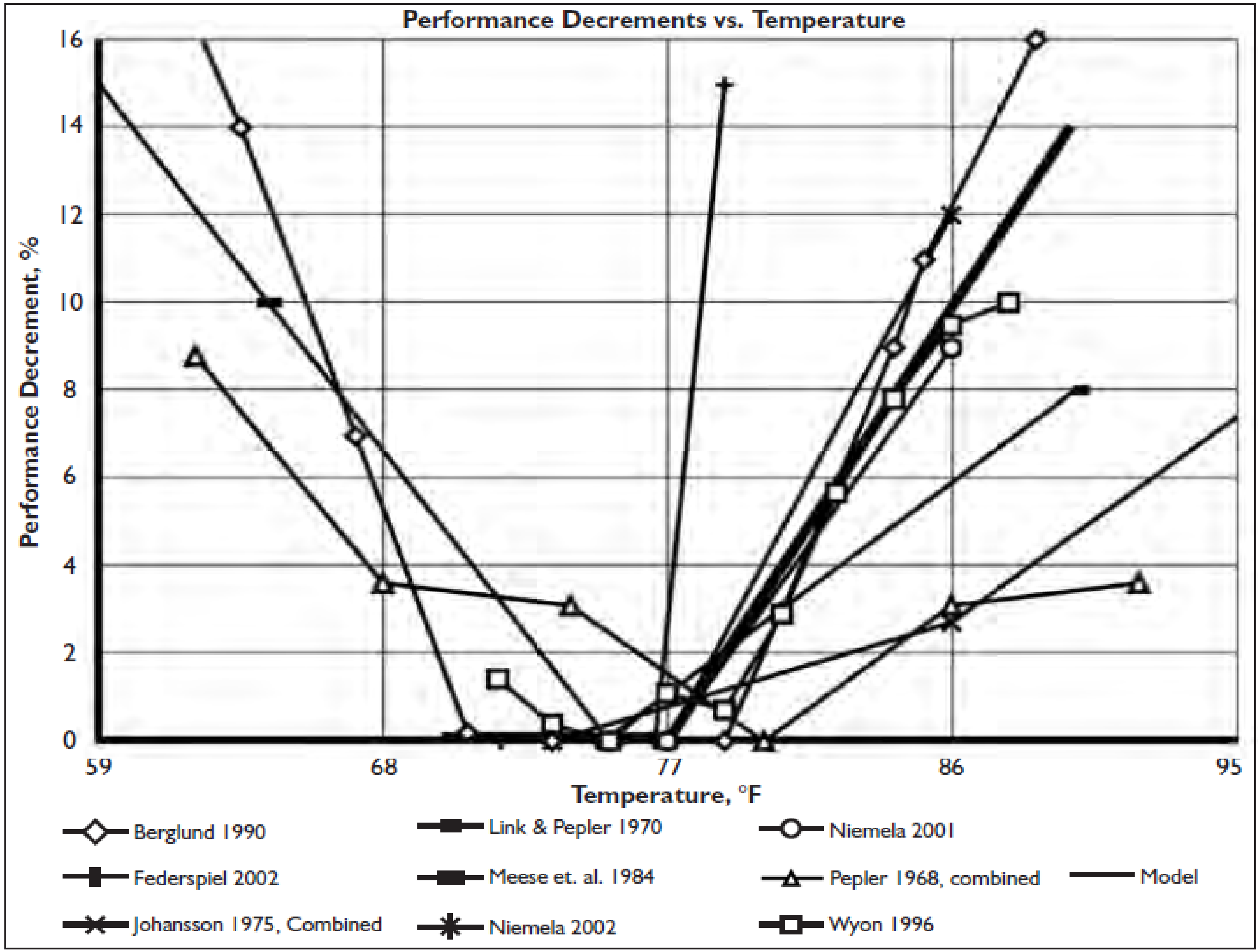
Finding the Balance of Maintaining Thermal Comfort and Energy Demand, Consumption

Example: Implementing Demand Response in an Existing Campus

- Project goals: Study how could automated demand response measures be implemented in existing campus of buildings with wide range of technologies available and real-time price tariff
- First example of test case: Saturday 7 June 2014 (low occupancy, limited ‘risk’)
  - Changed zone set points by +3° F
  - Changed supply air set point also +3° F
  - Changed upper limit for AHU fan speed from 100% to 90% of maximum (when possible)
  - Thermal comfort survey

Lessons Learned from this Test

- Perhaps temperature setpoints overall could be altered, or at least during higher cost time periods?
- Timing and scheduling
  - What are the optimal setpoint changes?
  - What times to start and stop?
  - How to avoid the rebound effect (‘soft-start’)?
- Most difficult… Need to be adaptable to the technologies in place
  - How to implement with automation and controls not designed for ‘automated’ demand response


Performance Decrements vs. Temperature
Performance Decrement, %
0
2
4
6
8
10
12
14
16
59
68
77
86
95
Temperature, °F
Berglund 1990
Link & Pepler 1970
Niemela 2001
Federspiel 2002
Meese et. al. 1984
Pepler 1968, combined
Model
Johansson 1975, Combined
Niemela 2002
Wyon 1996

“People Costs” are the Highest

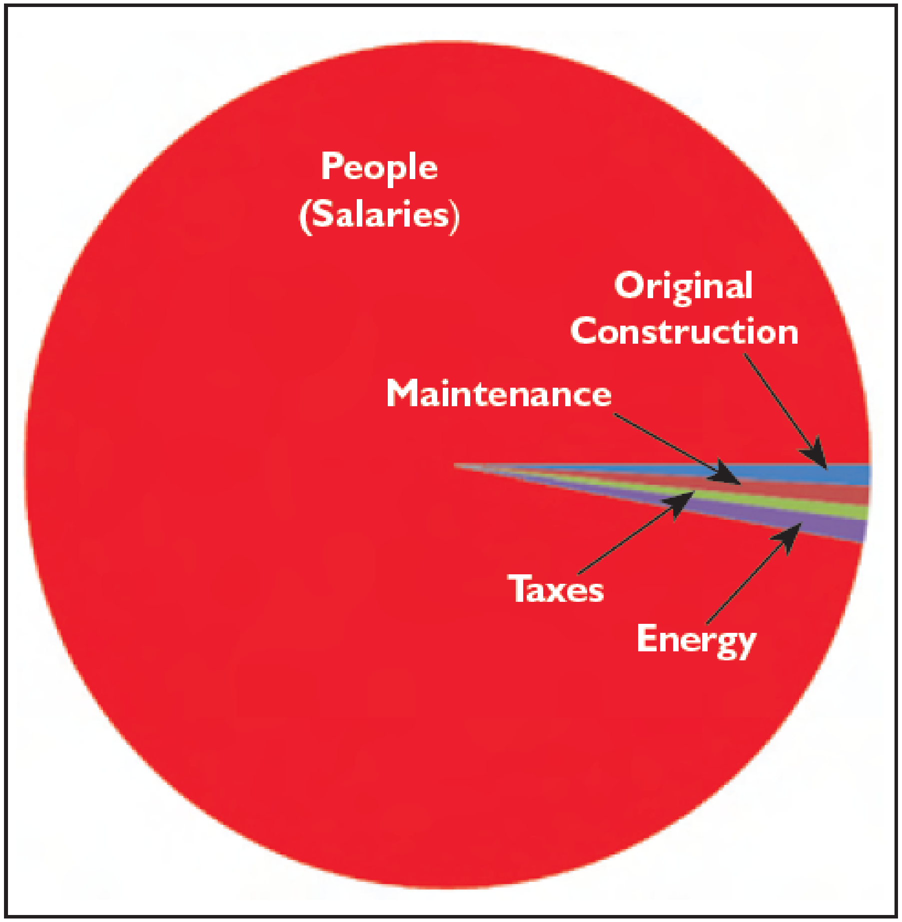


Figure 2: Life-cycle building costs breakdown with people (salaries).

Tom, S. 2008. “Managing Energy and Comfort”, ASHRAE Journal 50(6):18-26.

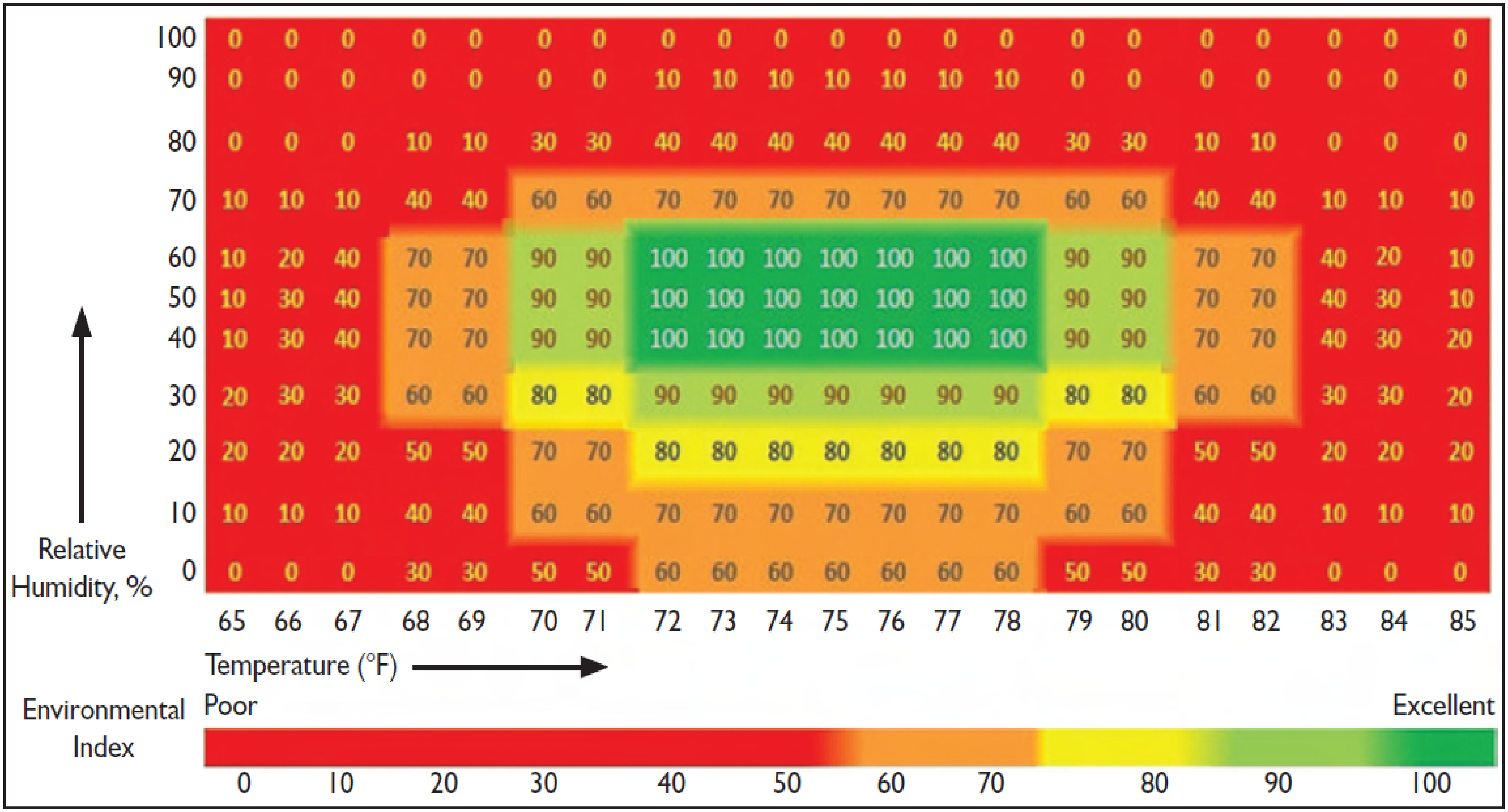
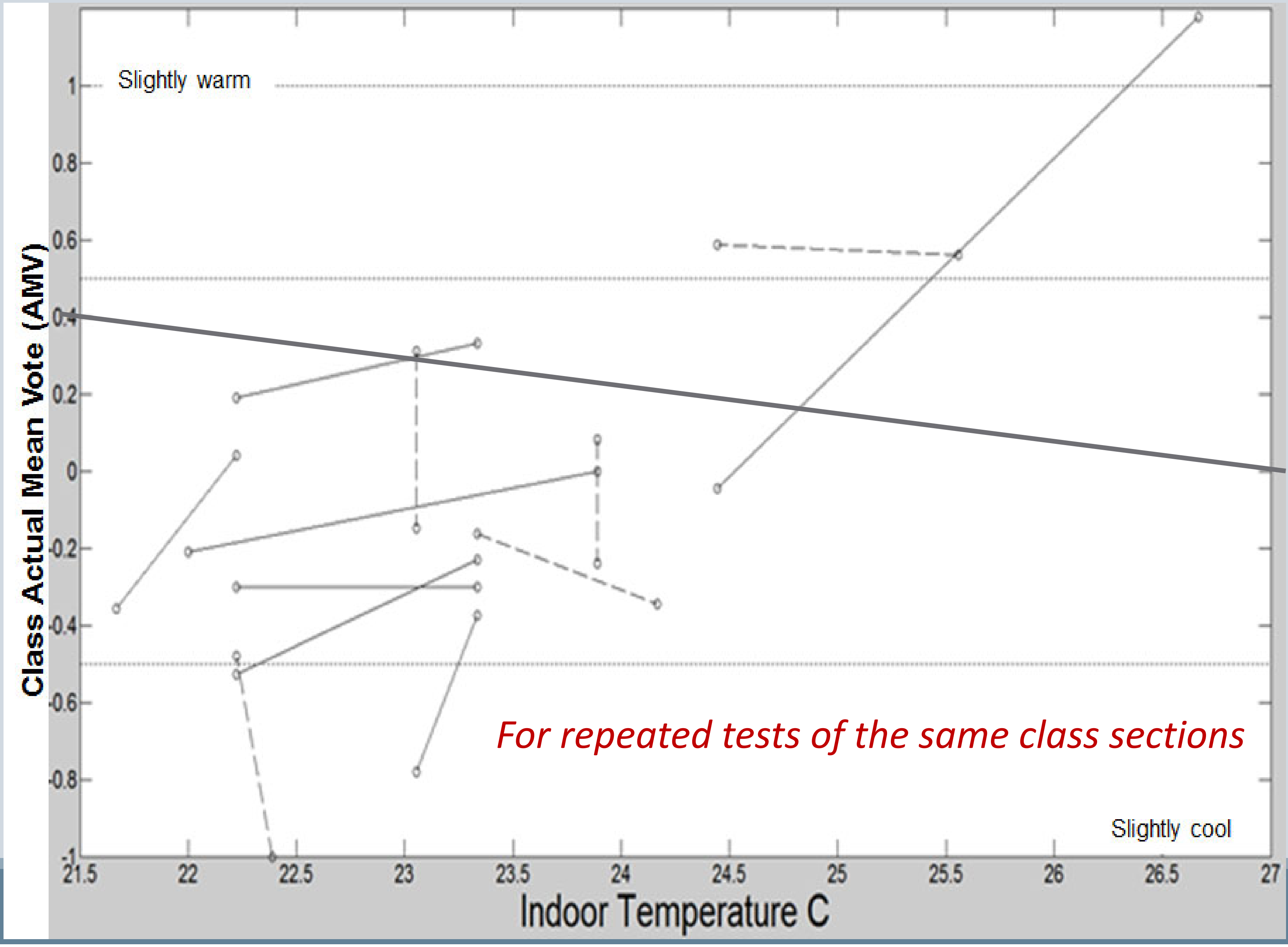


Figure 5: Environmental (comfort) index for temperature and humidity.

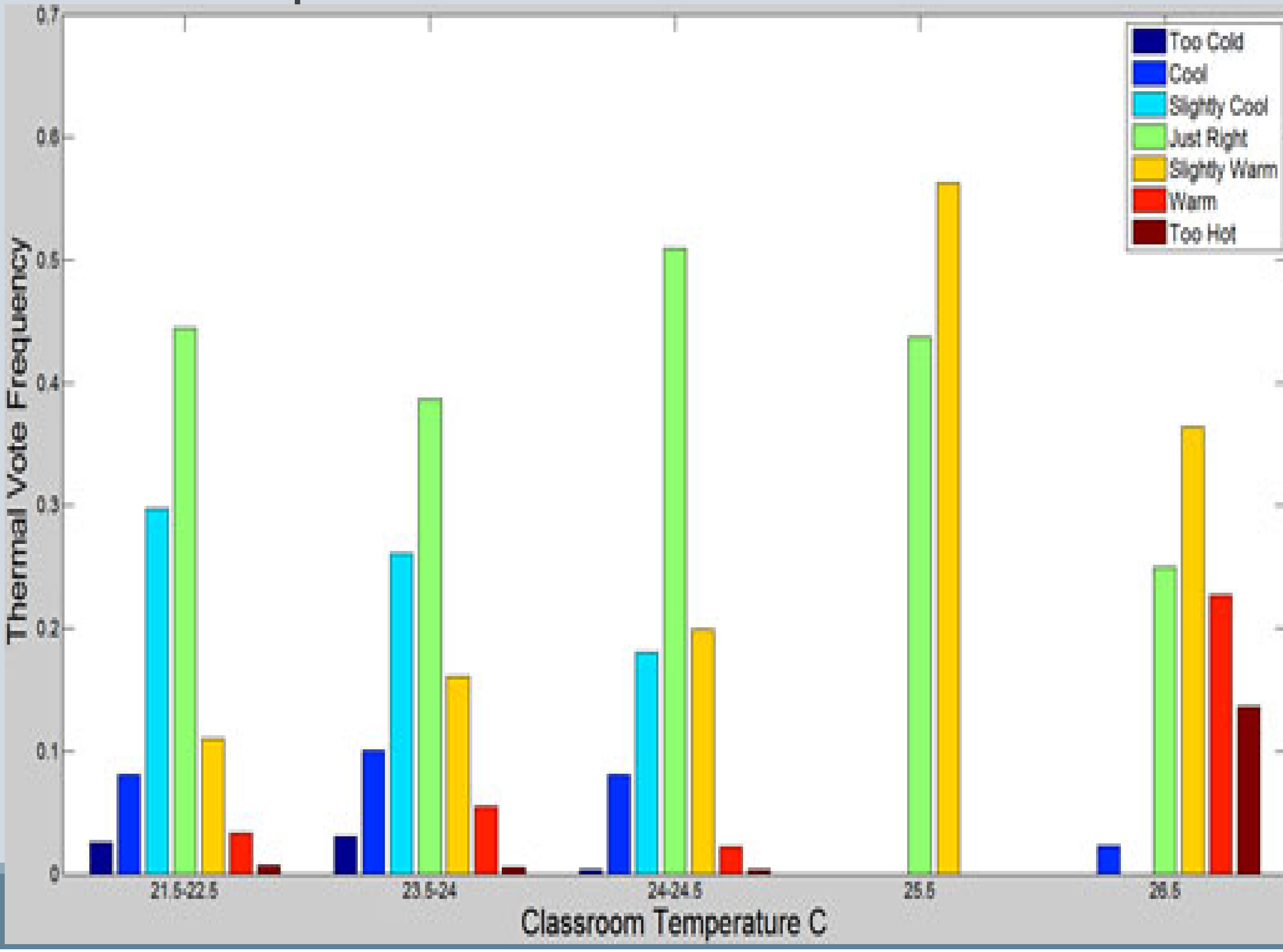
Tom, S. 2008. "Managing Energy and Comfort", ASHRAE Journal 50(6):18-26.

Example Field Test Results in Real-World Settings

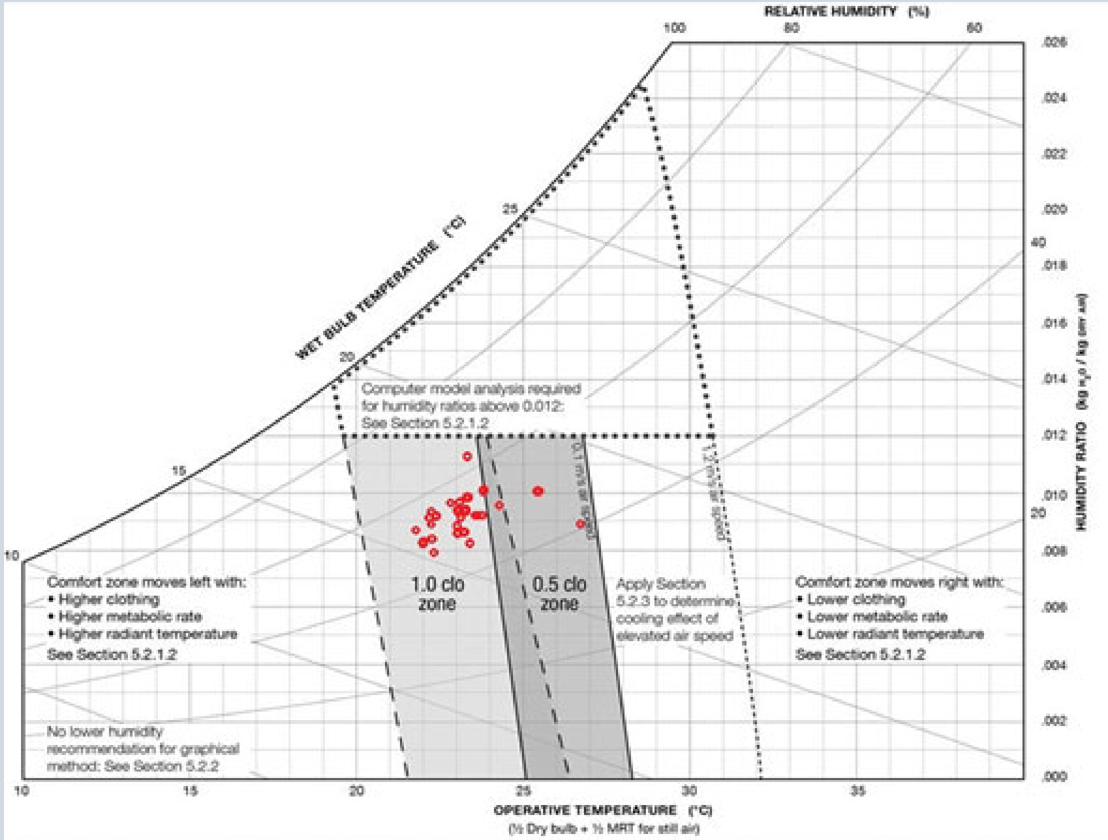
Actual Mean Vote vs. Zone Temp



Thermal Comfort Vote Frequency vs. Temperature



Classroom Testing Conditions



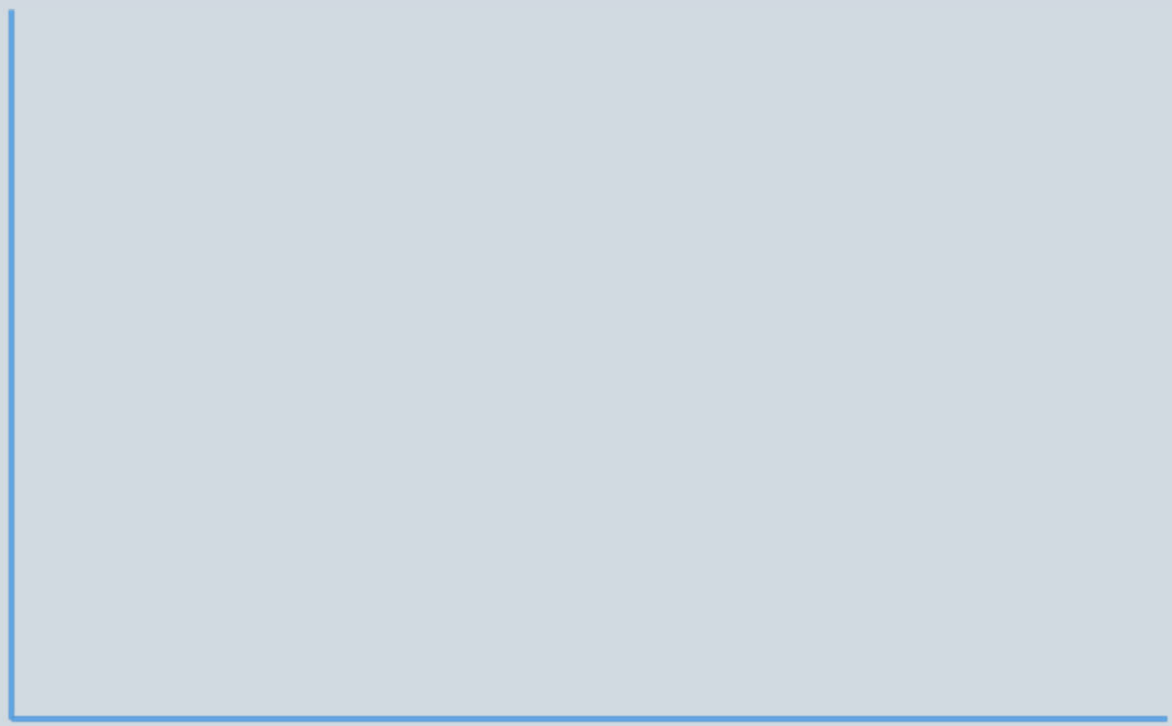
An Optimization Model?

Could we develop a method to optimize:

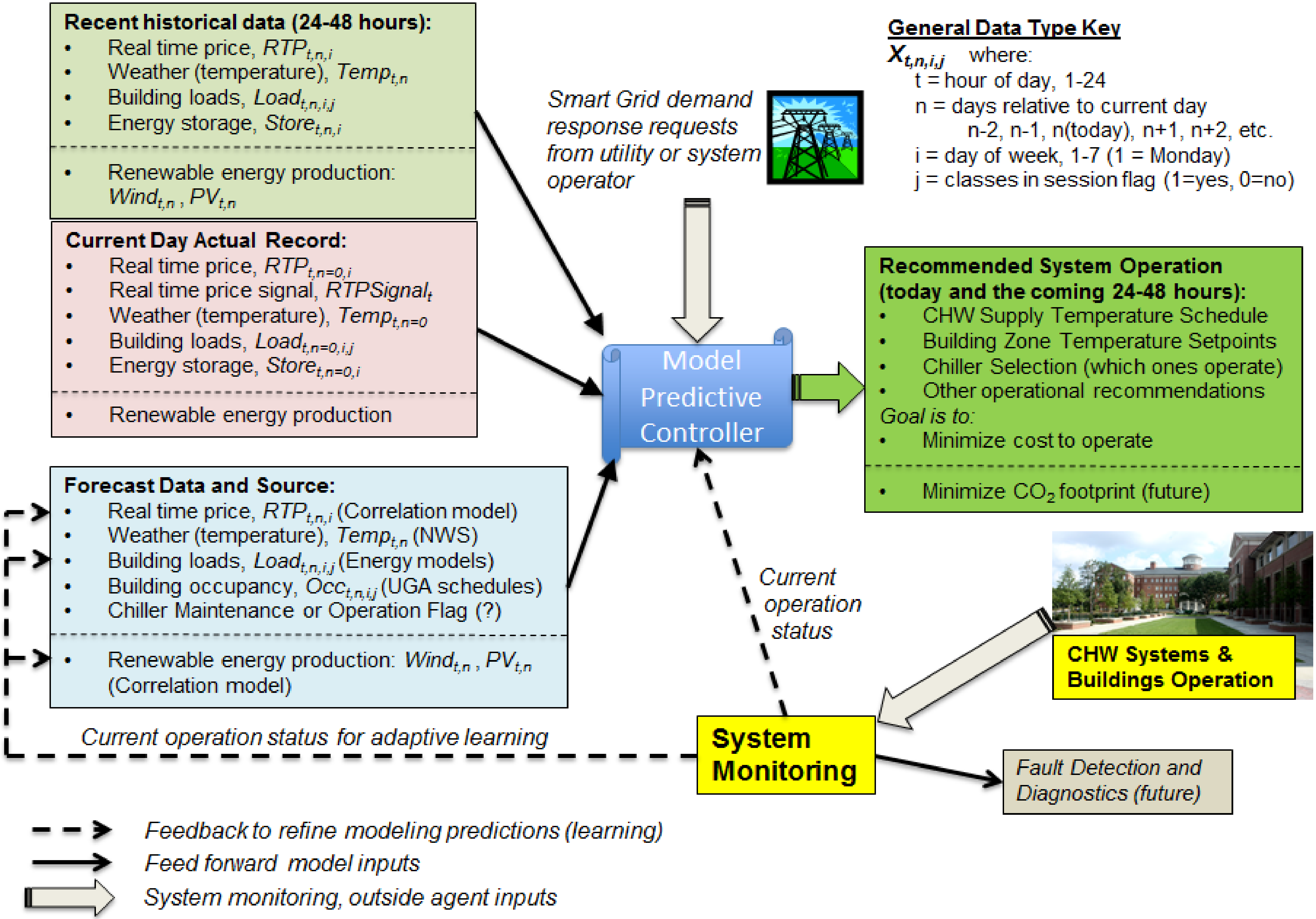
- $f = \max(\text{thermal comfort, energy consumption,}$ [and productivity?])
- How would you assign a "weight" to each of these?

$$Optimum = \omega \cdot Predicted\ energy\ costs + (1 - \omega) \cdot Predicted\ thermal\ comfort$$

What weighting function?



Model Predictive Control of a Single Building or District Energy System



Questions, Answers

For you:

- Is it possible to develop the optimization model (and apply this to building control)?

For me:

?

Thank You!

Other comments, questions, concerns, advice …

Dr. Tom Lawrence, P.E., LEED-AP
lawrence@engr.uga.edu