Distributed Control of Residential Energy Systems (DCRES)

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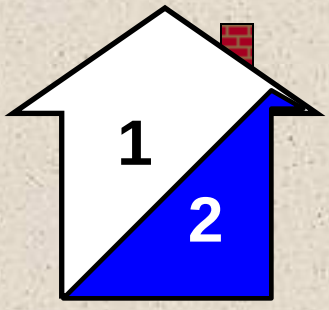
Motivation



- Residential Space Heating and Cooling
  - Typically 50% of household's electricity consumption
  - 9 Quads of United States energy usage (9%)
  - Results in 137 million metric tons of carbon equivalent emissions (triggers warmer weather)
  - Price of electricity on the rise
- Wireless Technology
  - Advancing field
  - High performance networks can be adapted to wide ranges of disciplines at low costs

Background Information

- Thermostat control strategies may offer great opportunities to cut down energy consumption
- Thermal comfort (PMV+PPD) can be a better metric to control the actuation of heating and cooling systems than traditional temperature threshold logic
- Wireless network technology has been utilized in HVAC applications to reduce large commercial building energy consumption
- Control strategies using comfort and a wireless sensor network have been tested residentially in a dry climate (California) for cooling systems (79% normalized energy savings)

Objective

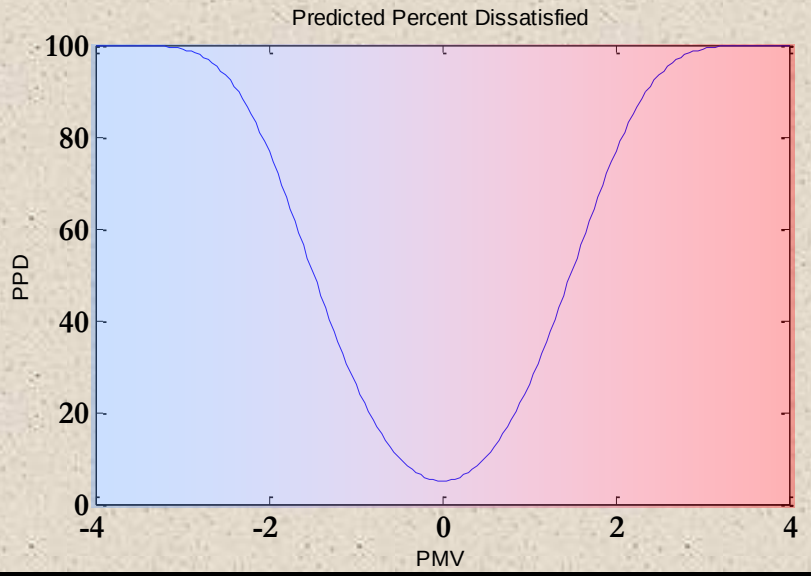
To test heating and cooling system control strategies for a residential unit in the mid-Atlantic climate region

- Wireless sensor network
- ASHRAE defined Predicted Percent Dissatisfied (PPD)
- Strategies to optimize comfort and reduce energy consumption
- Test strategies in building energy simulation software

Thermal Comfort

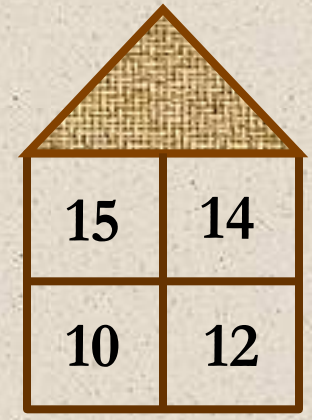
- P.O. Fanger developed definition of comfort
  - Biological heat transfer with the local environment
  - Determined using air and wall temperature, relative humidity, clothing level, activity, relative air velocity
  - Used to define ASHRAE Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD)

PMV	Thermal Sensitivity
> -3.5	very cold
-2.6 - -3.5	cold
-1.6 - -2.5	cool
-0.6 - -1.5	slightly cool
-0.5 - 0.5	neutral (comfortable)
0.6-1.5	slightly warm
1.6 - 2.5	warm
2.6 - 3.5	hot
> 3.6	very hot



Control Strategies (Cooling)

- **Baseline (BASE)**
  - Designed to mimic stock thermostat with 1°F dead band
  - Turns on cooling when hallway temperature reaches 25°C [77°F]
  - Turns off when temperature drops below 24.4°C [76°F]
- **Average All (AVE)**
  - Read sensor measurements and determine the PPD of each room
  - Average all the room's PPD
  - Determine if cooling is needed based off of a threshold PPD value of 12% (cool if PPD is 12 or above)



AVEPPD = 12.75

Cooling ON

Control Strategies (Cooling)

- **Minimize the Probability for Dissatisfaction (MND)**
  - Sum up all the room's PPD
  - Calculate how a temperature decrease of 0.25 °C [0.45 °F] would affect this aggregate PPD
  - If a temperature change will lower the PPD then the cooling system is triggered
- **Maximizing the Number of Rooms below a Threshold PPD (MXR)**
  - Determine how many rooms are above the threshold PPD of 12
  - Calculate how a temperature decrease of 0.25 °C [0.45 °F] would affect each room's PPD
  - If a temperature change will increase the number of rooms below the threshold PPD then the cooling system is triggered

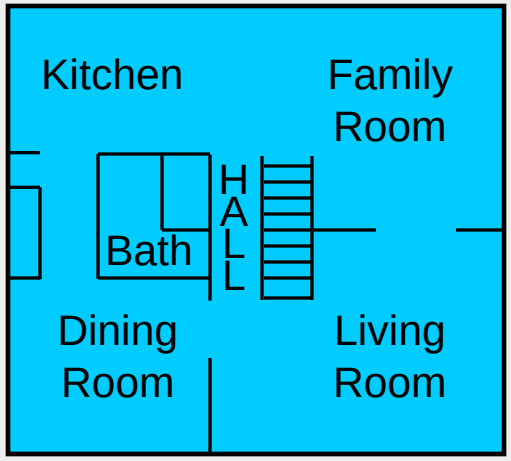
Control Strategies (Cooling)

- **Comfort Baseline (COM)**
  - Uses comfort levels rather than temperature as the threshold to mimic a stock thermostat
  - Turns on cooling when hallway PPD reaches 8
  - Turns off when hallway PPD drops below 5.4
- **Shifted Minimize the Probability for Dissatisfaction (MNDV2)**
  - The same as MND but subtract 1 °C from every measured temperature to shift the PPD curve for a warmer control point
  - If a predicted temperature change of 0.25 °C will lower the aggregate PPD then the cooling system is triggered

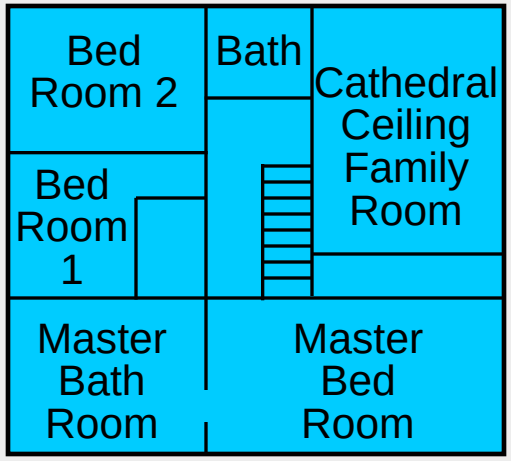
Experiment Setup

- **Hardware setup**
  - Crossbow IRIS wireless sensor motes
  - 3 Ton Direct Expansion (R22) HVAC system
  - Computer actuation via parallel port and relays
- **Software**
  - Communication with remote computers
  - Wireless sensor network acquires real-time sensor data
  - Coded control strategies
  - Decision interval to turn system on or off every 10 minutes

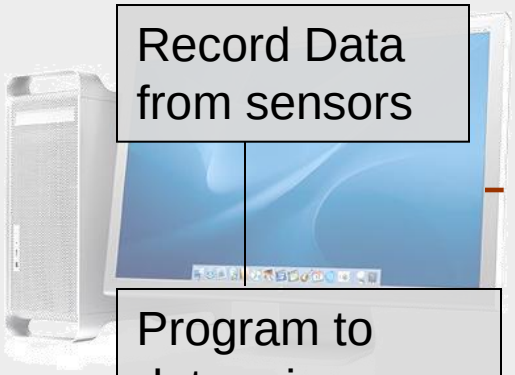
Residence: 2200 ft^2, 2 Storey, Rockville, MD



1st Floor



2nd Floor



Record Data from sensors

Program to determine command for HVAC system

HVAC Unit

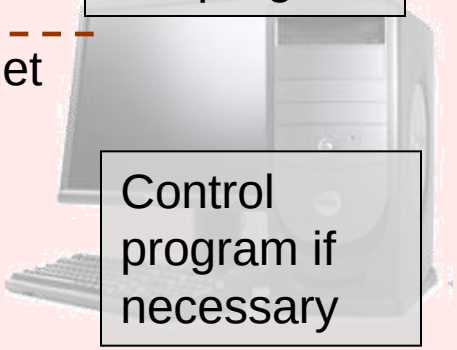
Turn on/off

Current Thermostat

U. Maryland

View Data and program

Via internet



Control program if necessary

Or iPhone

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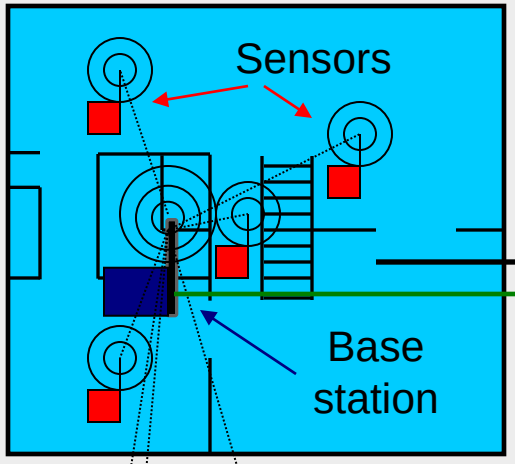

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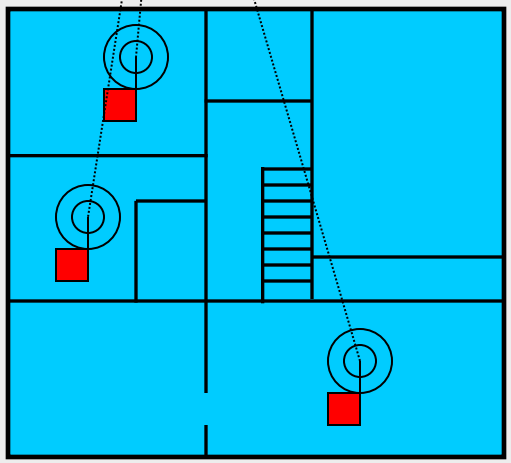

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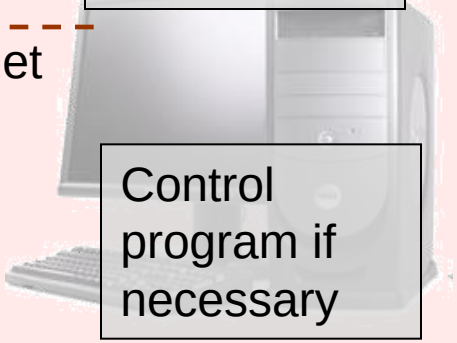

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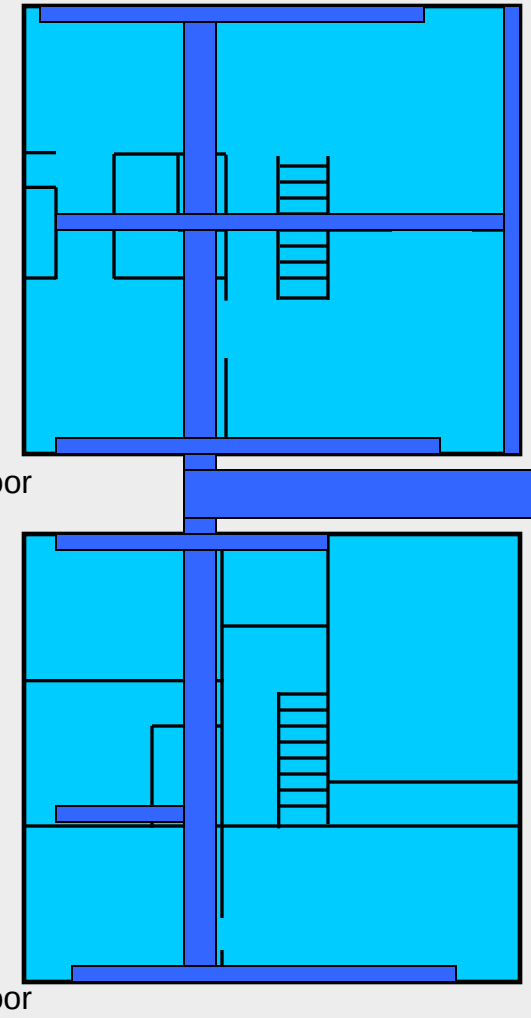

HVAC Unit

Current Thermostat

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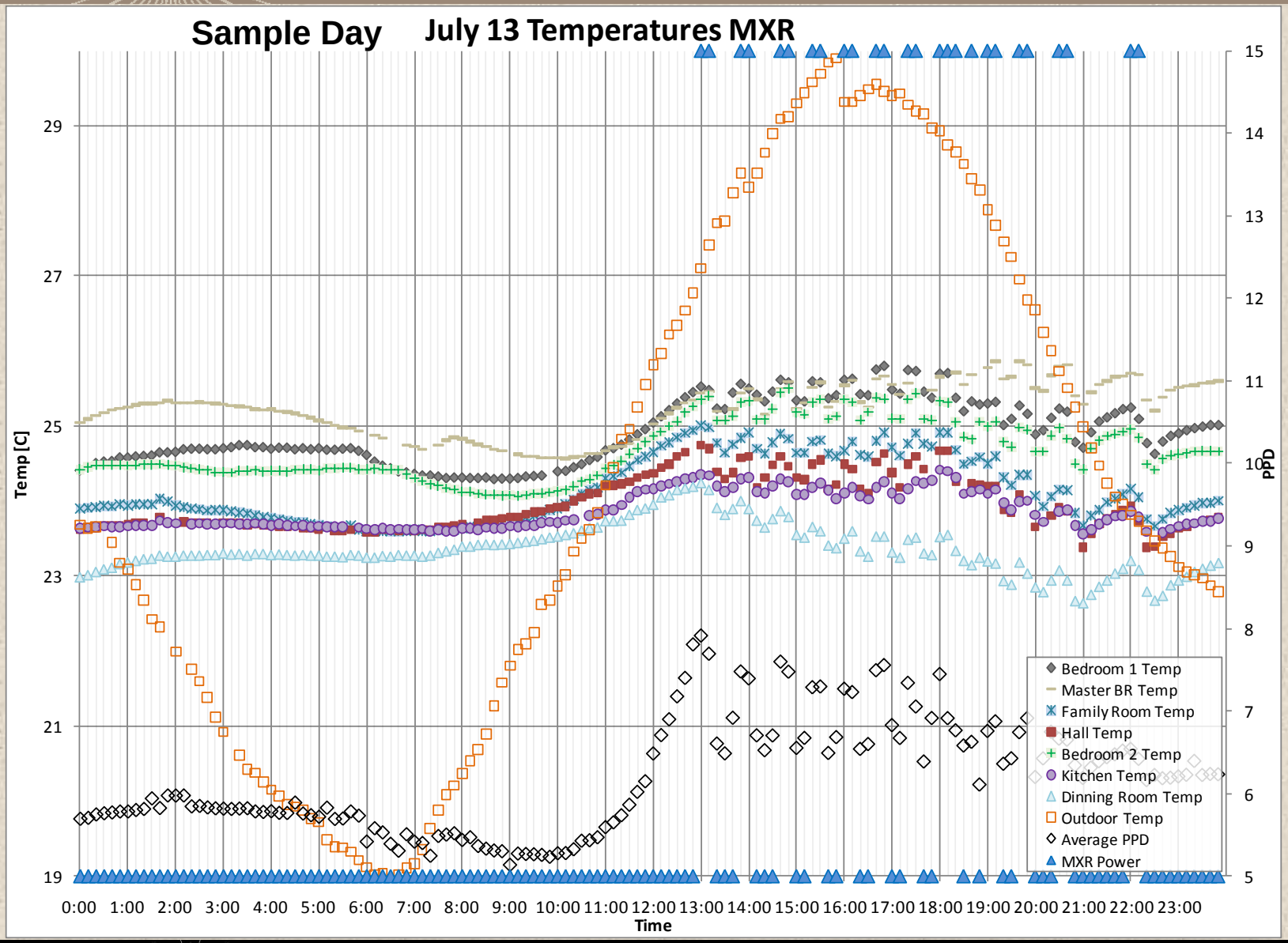
Sample Day
July 13 Temperatures MXR
Temp [C]
PPD
Time
29
27
25
23
21
19
15
14
13
12
11
10
9
8
7
6
5
0:00
1:00
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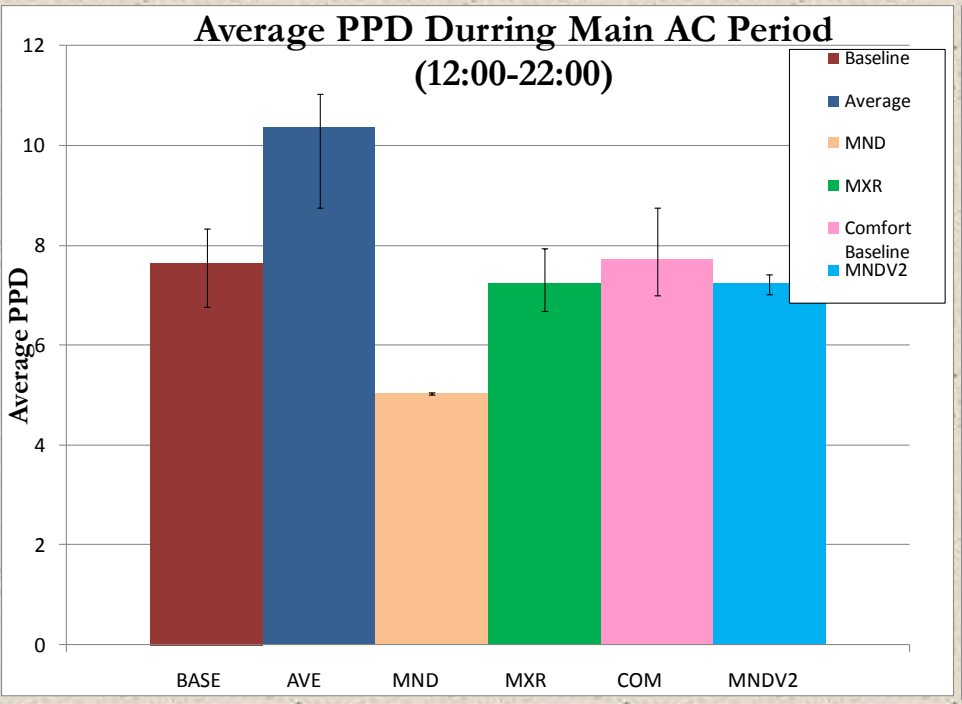
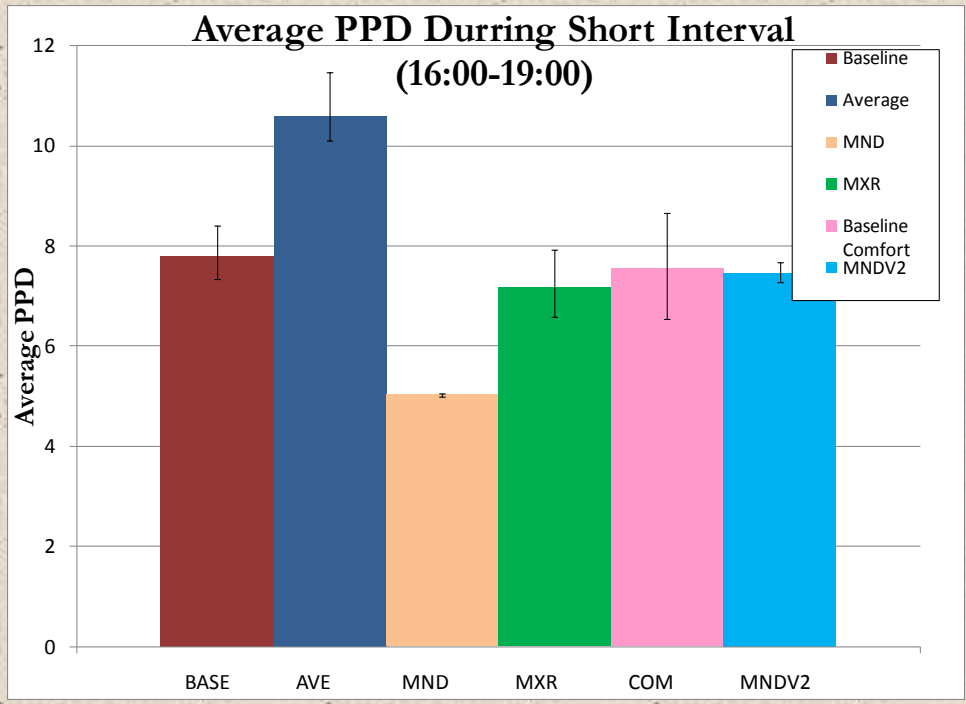
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Bedroom 1 Temp
Master BR Temp
Family Room Temp
Hall Temp
Bedroom 2 Temp
Kitchen Temp
Dinning Room Temp
Outdoor Temp
Average PPD
MXR Power

Comparing the Strategies

- A specific strategy will control cooling for the entire 24 hour day but there are varying starting and outdoor conditions
  - Use intervals where starting and ending indoor conditions are the same
  - Use Cooling Degree Days (CDD) and Cooling Degree Intervals (CDI) from 19 C to account for different outdoor conditions
  - Shift the CDI interval to account for the temperature lag due to the thermal mass of the house
  - Normalize the duty cycle between strategies that operate at different comfort levels with a correction factor

Comparing the Comfort Levels Between Strategies



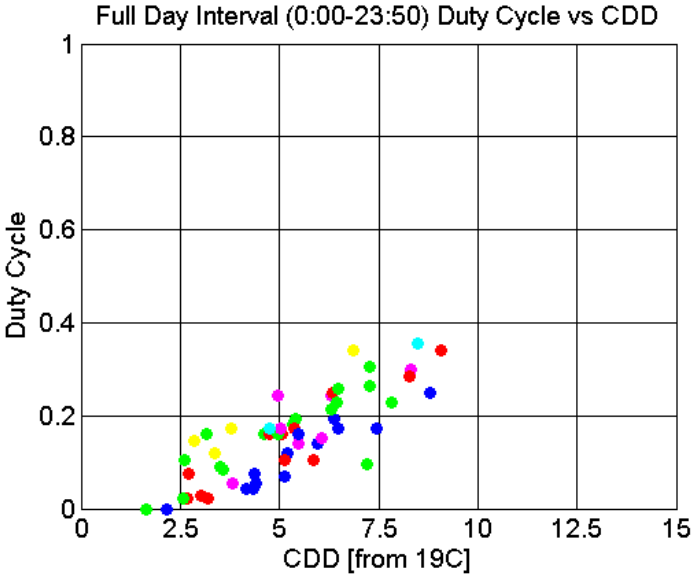


Indoor Ave PPD	BASE	AVE	MND	MXR	COM	MNDV2
Average	7.65	10.35	5.02	7.22	7.72	7.22
Min	6.76	8.75	5.01	6.69	7.00	7.02
Max	8.34	11.03	5.05	7.93	8.75	7.42
STDV	0.58	0.68	0.02	0.46	0.61	0.29

Indoor Ave PPD	BASE	AVE	MND	MXR	COM	MNDV2
Average	7.81	10.59	5.03	7.18	7.54	7.48
Min	7.35	10.12	5.02	6.59	6.55	7.28
Max	8.41	11.46	5.06	7.93	8.66	7.68
STDV	0.35	0.37	0.02	0.40	0.69	0.28

Full Day Interval

Date	16-Jun	23-Jun	25-Jun	29-Jun	30-Jun	1-Jul	2-Jul	3-Jul	4-Jul	5-Jul	6-Jul	7-Jul
Duty Cycle	0.08	0.16	0.14	0.04	0.17	0.08	0.02	0.00	0.12	0.00	0.03	0.07
CDD	2.71	4.61	5.94	4.17	3.78	3.57	2.68	2.15	3.37	1.63	3.03	5.13
Average PPD	8.40	5.31	8.33	6.57	5.06	5.61	6.01	6.07	5.03	5.09	7.24	7.55
Date	8-Jul	9-Jul	10-Jul	11-Jul	12-Jul	13-Jul	15-Jul	16-Jul	17-Jul	19-Jul	20-Jul	21-Jul
Duty Cycle	0.15	0.02	0.02	0.06	0.34	0.18	0.16	0.30	0.12	0.16	0.06	0.16
CDD	2.85	2.57	3.20	4.42	6.86	5.33	4.96	8.30	5.20	3.18	3.82	5.08
Average PPD	5.09	5.57	6.26	7.50	5.07	5.32	8.53	9.64	10.22	6.44	6.57	7.26
Date	22-Jul	24-Jul	25-Jul	27-Jul	29-Jul	30-Jul	31-Jul	1-Aug	2-Aug	3-Aug	4-Aug	5-Aug
Duty Cycle	0.17	0.16	0.16	0.24	0.25	0.19	0.19	0.17	0.10	0.14	0.22	0.10
CDD	6.47	4.75	4.95	6.32	6.33	6.38	5.40	5.36	5.13	5.47	6.32	5.86
Average PPD	10.16	7.01	6.51	8.17	8.42	9.90	8.12	7.47	7.90	7.92	6.60	6.91
Date	6-Aug	7-Aug	8-Aug	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	15-Aug	18-Aug	19-Aug
Duty Cycle	0.09	0.10	0.08	0.25	0.34	0.28	0.23	0.10	0.15	0.26	0.31	0.26
CDD	3.51	2.61	4.37	8.80	9.07	8.27	6.46	7.19	6.05	6.48	7.27	7.29
Average PPD	7.25	6.04	6.67	9.92	8.57	8.38	7.39	6.98	6.40	8.00	6.97	6.55
Date	20-Aug	21-Aug	22-Aug	23-Aug	24-Aug	26-Aug	27-Aug	28-Aug	29-Aug			
Duty Cycle	0.35	0.17	0.17	0.24	0.17	0.26	0.23	0.04	0.16			
CDD	8.47	7.44	5.01	4.96	4.75	6.48	7.82	4.35	5.47			
Average PPD	7.06	10.12	7.58	6.84	6.78	7.04	6.48	8.61	10.84			



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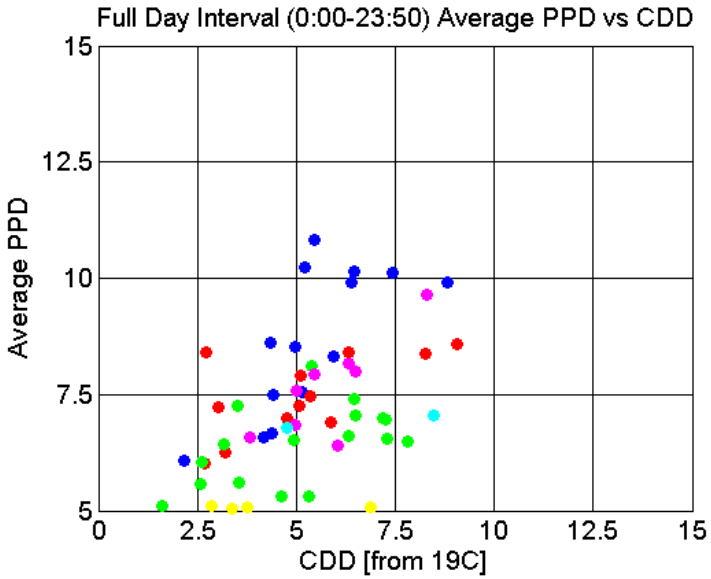
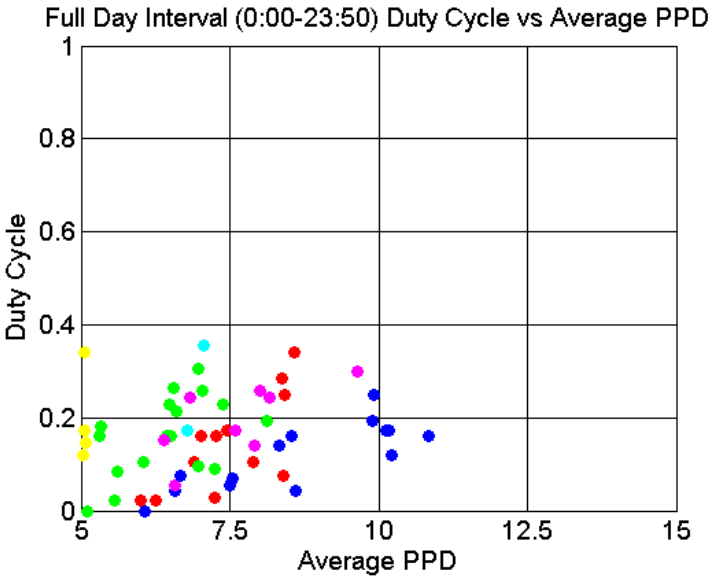
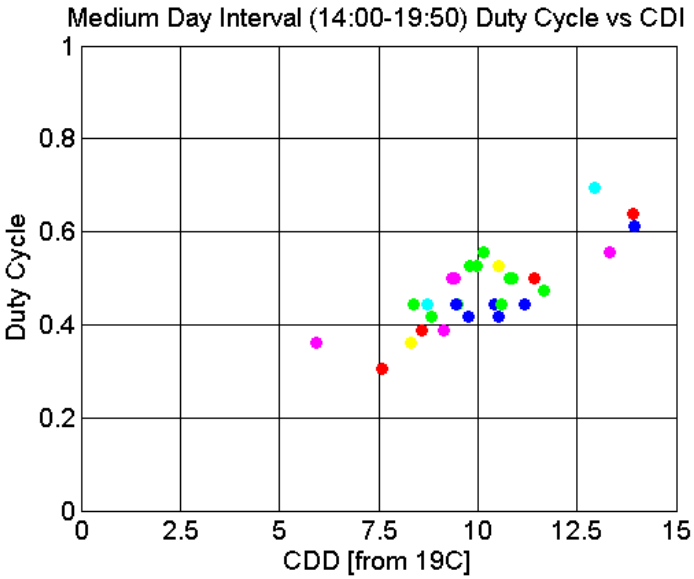


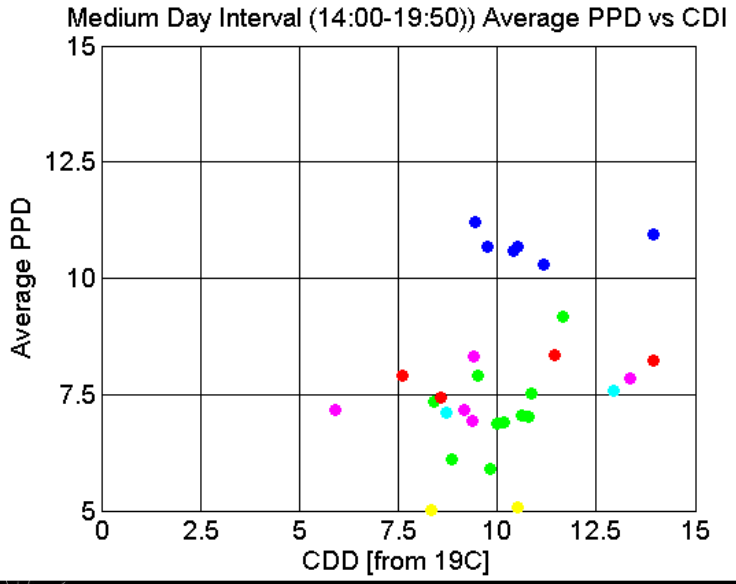


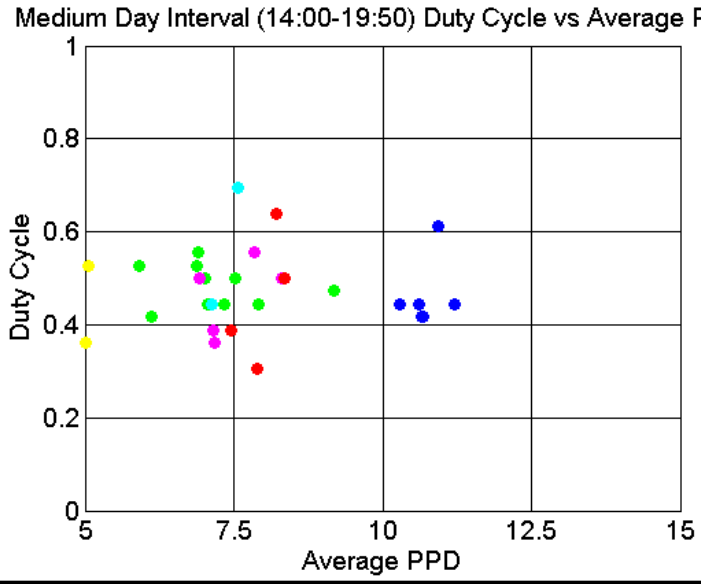
Medium Day Interval

Date	23-Jun	25-Jun	30-Jun	12-Jul	13-Jul	15-Jul	16-Jul	19-Jul	21-Jul	22-Jul
Duty Cycle	0.42	0.44	0.36	0.53	0.53	0.44	0.56	0.44	0.39	0.42
CD Interval	8.84	11.18	8.32	10.53	9.81	10.42	13.34	8.40	8.58	10.51
Average PPD	6.11	10.29	5.02	5.06	5.90	10.60	7.84	7.34	7.45	10.69
Date	25-Jul	27-Jul	29-Jul	30-Jul	4-Aug	9-Aug	10-Aug	11-Aug	12-Aug	14-Aug
Duty Cycle	0.44	0.50	0.31	0.42	0.50	0.61	0.64	0.50	0.44	0.39
CD Interval	10.60	9.40	7.60	9.75	10.79	13.96	13.93	11.44	9.50	9.16
Average PPD	7.06	8.32	7.89	10.67	7.02	10.93	8.22	8.36	7.92	7.16
Date	18-Aug	19-Aug	20-Aug	22-Aug	23-Aug	24-Aug	26-Aug	27-Aug	29-Aug	
Duty Cycle	0.53	0.56	0.69	0.36	0.50	0.44	0.47	0.50	0.44	
CD Interval	9.99	10.16	12.96	5.92	9.37	8.72	11.66	10.87	9.44	
Average PPD	6.87	6.89	7.58	7.18	6.93	7.12	9.17	7.51	11.20	



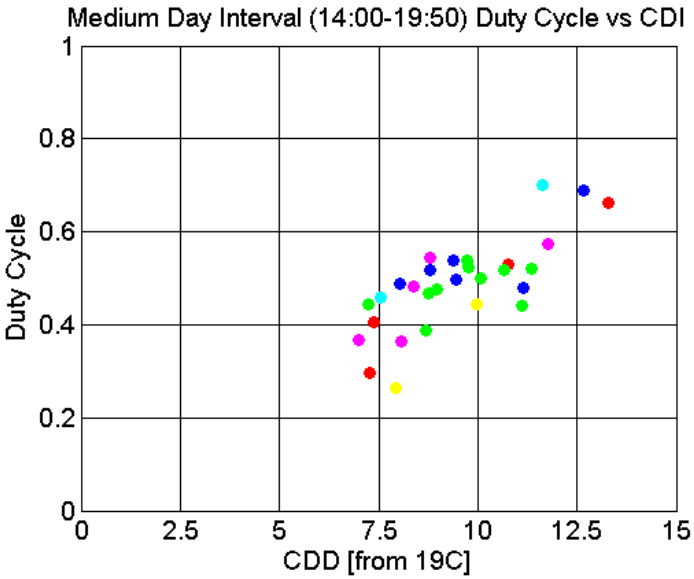
Red = Baseline
Blue = Ave All
Yellow = MND
Green = MXR
Pink = Baseline Comfort
Light Blue = MNDV2 (-1degree)





Medium Day Interval With Correction Factor

Date	23-Jun	25-Jun	30-Jun	12-Jul	13-Jul	15-Jul	16-Jul	19-Jul	21-Jul	22-Jul
Duty Cycle	0.39	0.48	0.27	0.44	0.47	0.54	0.57	0.44	0.41	0.50
CD Interval	8.70	11.15	7.92	9.97	8.77	9.37	11.75	7.23	7.36	9.46
Average PPD	6.11	10.29	5.02	5.06	5.90	10.60	7.84	7.34	7.45	10.69
Date	**25-Jul**	**27-Jul**	**29-Jul**	**30-Jul**	**4-Aug**	**9-Aug**	**10-Aug**	**11-Aug**	**12-Aug**	**14-Aug**
Duty Cycle	0.44	0.54	0.30	0.52	0.50	0.69	0.66	0.53	0.48	0.36
CD Interval	11.10	8.79	7.27	8.79	10.07	12.67	13.31	10.77	8.96	8.08
Average PPD	7.06	8.32	7.89	10.67	7.02	10.93	8.22	8.36	7.92	7.16
Date	**18-Aug**	**19-Aug**	**20-Aug**	**22-Aug**	**23-Aug**	**24-Aug**	**26-Aug**	**27-Aug**	**29-Aug**	
Duty Cycle	0.52	0.54	0.70	0.37	0.48	0.46	0.52	0.52	0.49	
CD Interval	11.35	9.73	11.63	7.01	8.38	7.56	10.66	9.76	8.02	
Average PPD	6.87	6.89	7.58	7.18	6.93	7.12	9.17	7.51	11.20	



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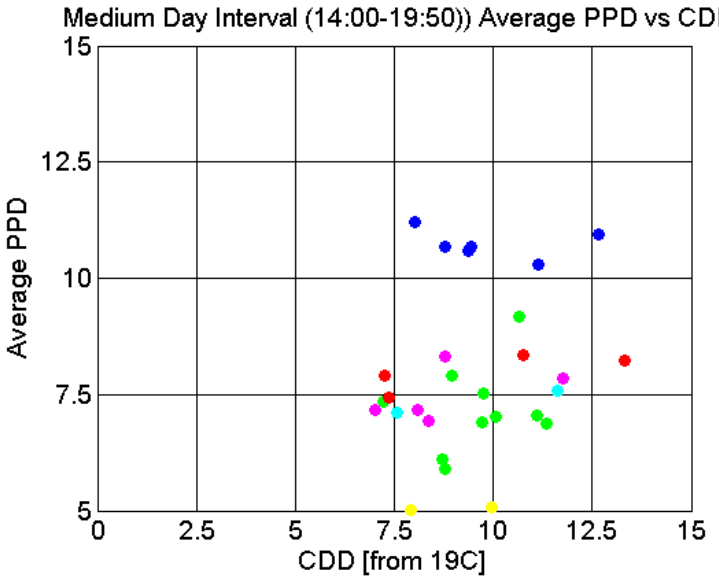
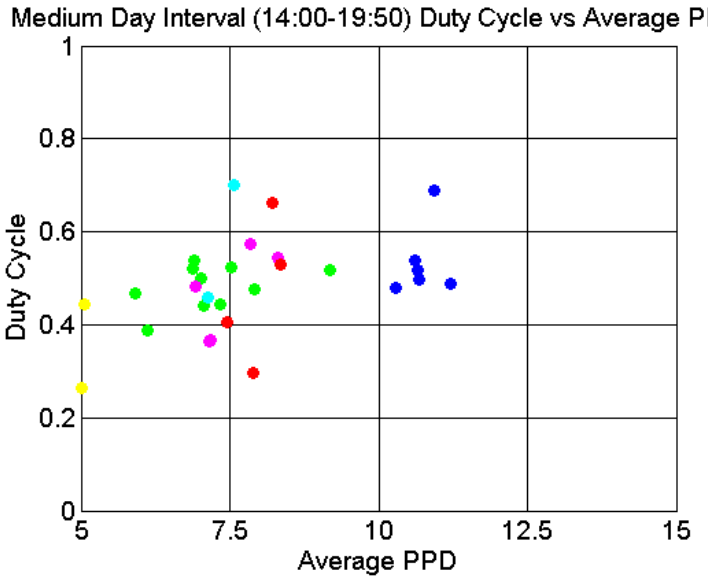
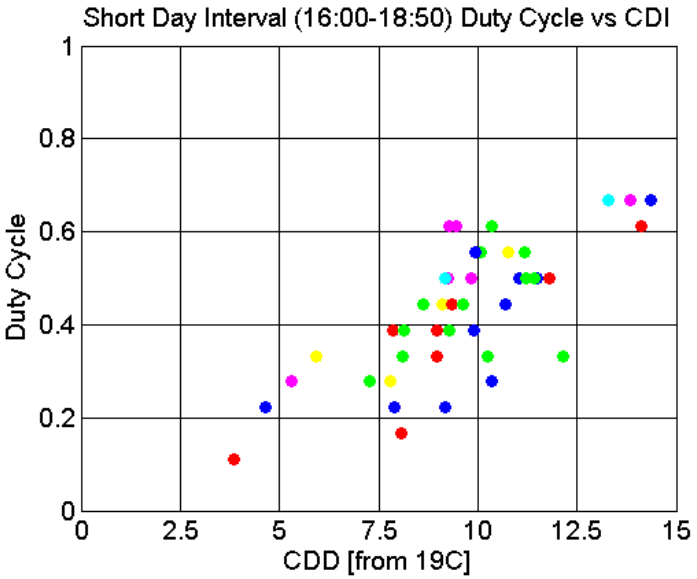




Short Day Interval

Date	16-Jun	23-Jun	25-Jun	29-Jun	30-Jun	1-Jul	4-Jul	7-Jul	8-Jul	11-Jul	12-Jul	13-Jul
Duty Cycle	0.11	0.39	0.50	0.22	0.44	0.28	0.28	0.28	0.33	0.22	0.56	0.56
CD Interval	3.85	9.26	11.50	9.17	9.09	7.26	7.81	10.36	5.93	7.89	10.78	10.07
Average PPD	8.41	6.14	10.12	10.57	5.03	5.68	5.02	10.46	5.02	10.31	5.06	5.91
Date	15-Jul	16-Jul	17-Jul	19-Jul	21-Jul	22-Jul	24-Jul	25-Jul	27-Jul	29-Jul	30-Jul	1-Aug
Duty Cycle	0.44	0.67	0.22	0.44	0.33	0.50	0.39	0.50	0.61	0.39	0.39	0.44
CD Interval	10.70	13.85	4.65	8.63	8.96	11.03	8.96	11.41	9.47	7.87	9.91	9.34
Average PPD	10.25	7.74	10.77	7.24	7.35	10.58	8.04	7.03	7.57	7.77	10.71	7.94
Date	2-Aug	3-Aug	4-Aug	5-Aug	7-Aug	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	18-Aug
Duty Cycle	0.17	0.61	0.50	0.39	0.33	0.67	0.61	0.50	0.44	0.33	0.50	0.39
CD Interval	8.08	9.28	11.21	8.98	8.11	14.35	14.11	11.80	9.63	10.25	9.24	8.16
Average PPD	7.36	8.66	6.89	7.52	8.23	10.64	8.07	7.86	7.93	7.31	7.23	6.59
Date	19-Aug	20-Aug	22-Aug	23-Aug	24-Aug	26-Aug	27-Aug	29-Aug				
Duty Cycle	0.61	0.67	0.28	0.50	0.50	0.33	0.56	0.56				
CD Interval	10.35	13.28	5.32	9.82	9.16	12.15	11.19	9.92				
Average PPD	6.99	7.68	7.52	6.55	7.28	9.46	7.41	11.46				



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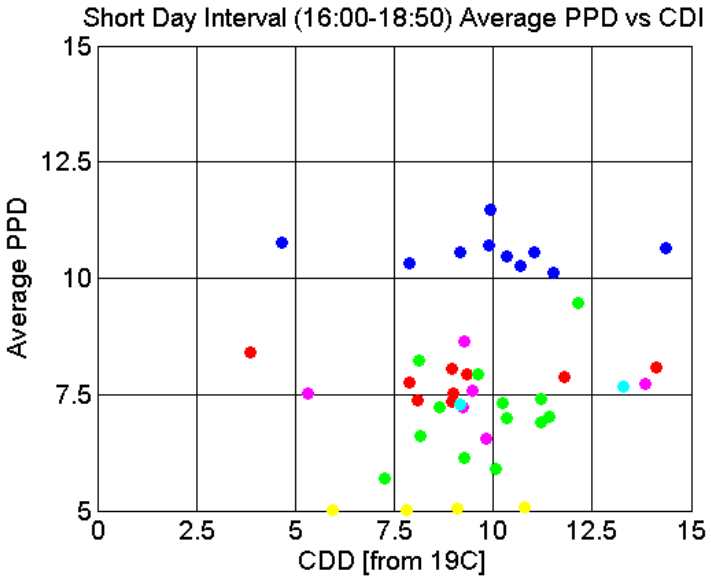
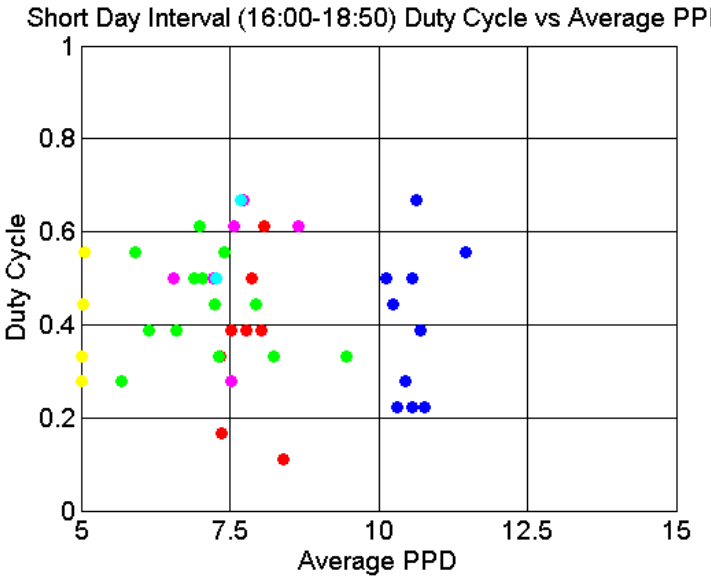
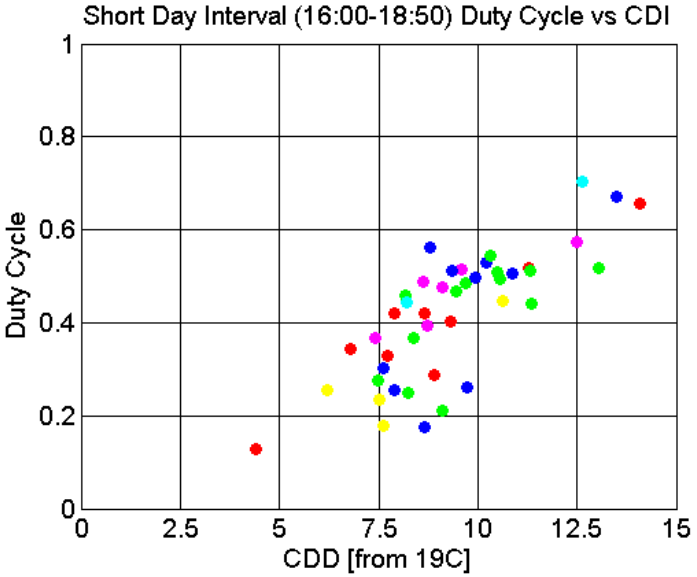
Green = MXR
Pink = Baseline Comfort
Light Blue = MNDV2 (-1degree)



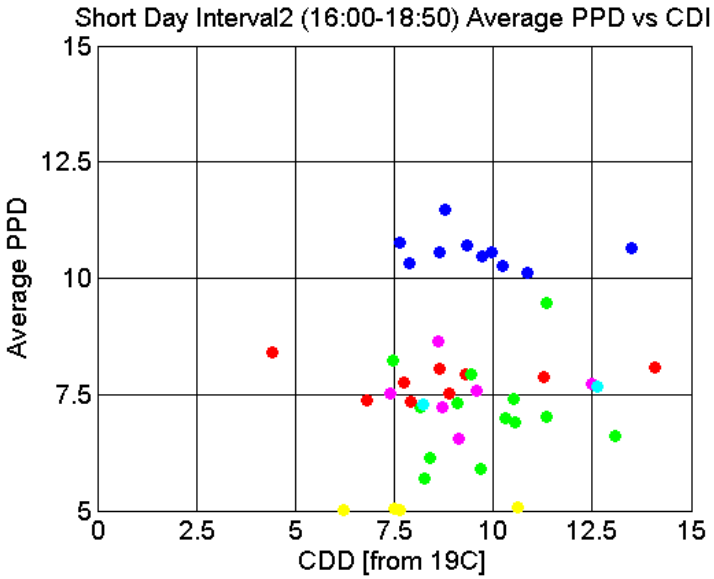


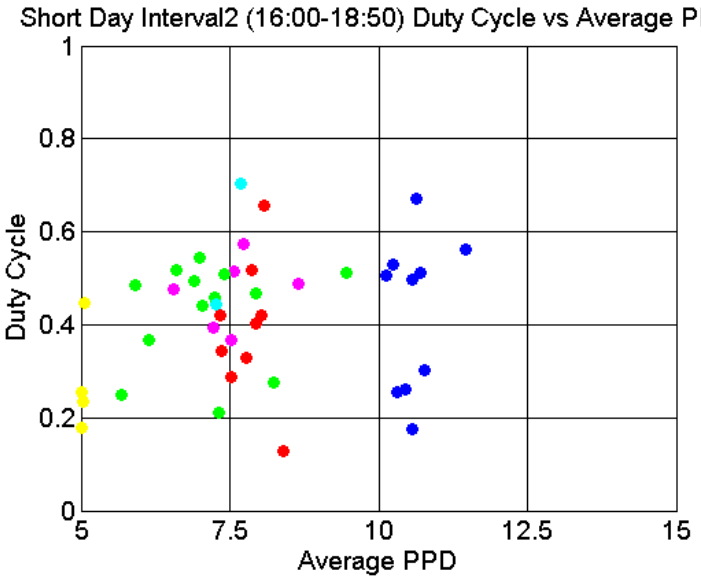
Short Day Interval With Correction Factor

Date	16-Jun	23-Jun	25-Jun	29-Jun	30-Jun	1-Jul	4-Jul	7-Jul	8-Jul	11-Jul	12-Jul	13-Jul
Duty Cycle	0.13	0.37	0.51	0.17	0.23	0.25	0.18	0.26	0.26	0.25	0.45	0.48
CD Interval	4.40	8.39	10.88	8.65	7.52	8.26	7.63	9.73	6.22	7.88	10.62	9.69
Average PPD	8.41	6.14	10.12	10.57	5.03	5.68	5.02	10.46	5.02	10.31	5.06	5.91
Date	15-Jul	16-Jul	17-Jul	19-Jul	21-Jul	22-Jul	24-Jul	25-Jul	27-Jul	29-Jul	30-Jul	1-Aug
Duty Cycle	0.53	0.57	0.30	0.46	0.42	0.50	0.42	0.44	0.51	0.33	0.51	0.40
CD Interval	10.23	12.50	7.63	8.17	7.91	9.95	8.65	11.35	9.58	7.74	9.34	9.30
Average PPD	10.25	7.74	10.77	7.24	7.35	10.58	8.04	7.03	7.57	7.77	10.71	7.94
Date	2-Aug	3-Aug	4-Aug	5-Aug	7-Aug	9-Aug	10-Aug	11-Aug	12-Aug	13-Aug	14-Aug	18-Aug
Duty Cycle	0.34	0.49	0.49	0.29	0.28	0.67	0.66	0.52	0.47	0.21	0.40	0.52
CD Interval	6.80	8.62	10.55	8.90	7.47	13.49	14.10	11.27	9.45	9.10	8.72	13.06
Average PPD	7.36	8.66	6.89	7.52	8.23	10.64	8.07	7.86	7.93	7.31	7.23	6.59
Date	19-Aug	20-Aug	22-Aug	23-Aug	24-Aug	26-Aug	27-Aug	29-Aug				
Duty Cycle	0.55	0.70	0.37	0.48	0.44	0.51	0.51	0.56				
CD Interval	10.32	12.63	7.40	9.12	8.21	11.33	10.50	8.79				
Average PPD	6.99	7.68	7.52	6.55	7.28	9.46	7.41	11.46				



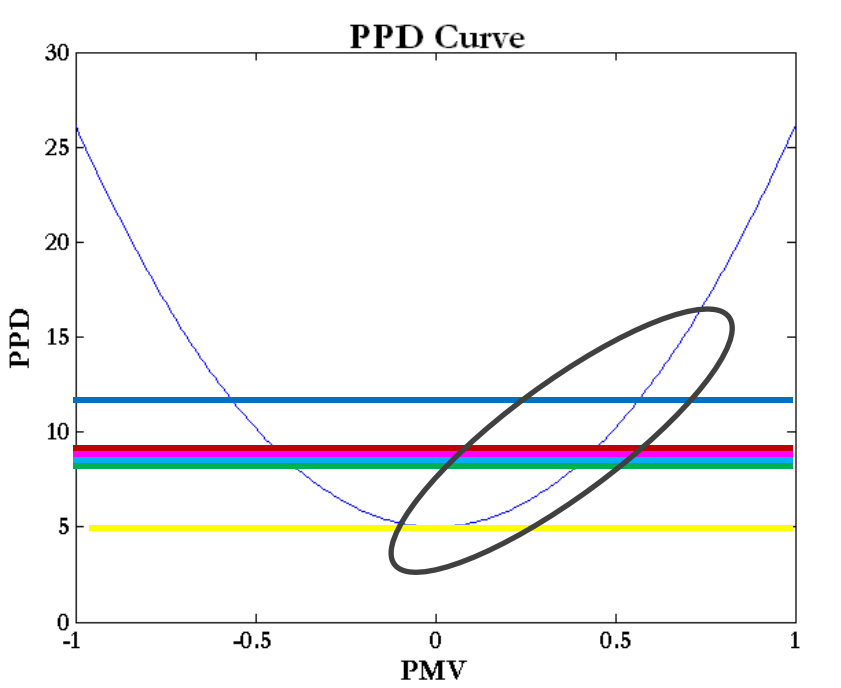
Red = Baseline
Blue = Ave All
Yellow = MND
Green = MXR
Pink = Baseline Comfort
Light Blue = MNDV2 (-1degree)





Analysis

- Different strategies operate on different levels of the PPD curve
- ΔT drives heat transfer so the larger the difference between the indoor and outdoor temperatures the higher the duty cycle
- Higher comfort (lower PPD) strategies keep the indoor temperature lower and have a higher duty cycle
- The correction factor levels the playing field but the difference in duty cycles are within the variation ~10-20%



Conclusions

- The strategies implemented this summer did not show large reductions in energy. Other experiments could have underestimated key information
  - Starting and outdoor conditions have a major impact on when and how the strategy will keep the house comfortable
  - The duty cycle is also dependent on the comfort level the strategies operate around
- More environmental information does not translate to energy savings or higher comfort
  - The Baseline verse the MXR strategy
  - The information would be more useful if there was control over the distribution of the conditioned air

Future Work

- Analyze the room-to-room differences in comfort levels for each of the strategies
- Perform similar experiments for heating in the winter
- Run simulations to validate experimental results and to determine what other mechanisms are involved in the energy consumption
- Consider techniques to pair the information gain achieved with the wireless sensors and control over the distribution of the conditioned air