# SMARTER -Smart Manager for Adaptive and Real-Time decisions in building clustERs


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## Introduction and Motivation

1. 40% of the energy and $CO_2$ emissions in the U.S. are due to buildings, more than any other industry sector;
2. The electricity consumption of the U.S. grew 1.7% annually from 1996 to 2006, and the expectation of total growth through 2030 will be 26% with buildings responsible for over 70% of all electricity consumption;
3. Smart grid technology is a cyber-enabled network of sensors, actuators, computers and power infrastructures that monitors and manages energy usage across a wide range of power loads in an effort to reduce cost and increase reliability and transparency;
4. Similar to micro-communities in a human society, neighboring buildings have the tendency to form clusters to exploit the economic opportunities provided by a smart grid, distributed power generation and storage devices, and to reduce overall primary energy consumption and peak time electricity consumption.

## Objectives

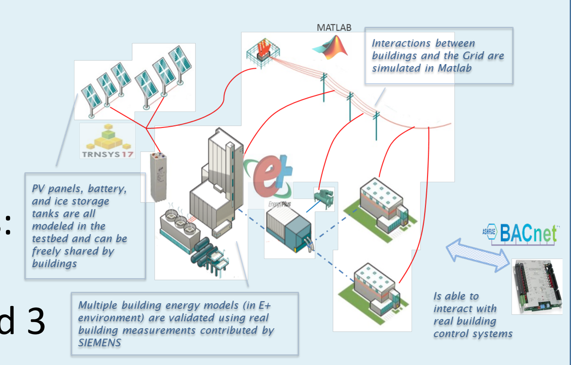
The CPS theme of this SMARTER project is to develop a decision framework, including appropriate methods and tools to enable real-time autonomous, robust, and optimal building energy system operation decisions for the next generation energy building clusters

**Task 1 Develop an Emulator for NetZero Energy Impact Building Clusters for Benchmarking and Evaluation of Different Operation Strategies**
**Task 2 Develop and Calibrate an Online Building Energy Consumption Model**
**Task 3 Developing Adaptive Decision Algorithms for Dynamic Operation Strategies**
**Task 4 Validation and Verification**

## Methods and Materials (Drexel)

**Task 1 NetZero Energy Building Clusters Emulator Development**

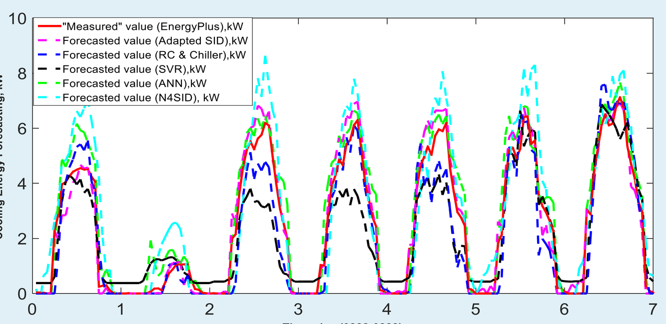
- Multiple experimentally calibrated building models
- Energy generation and storage models: PV, battery and ice tank
- Providing operation data for Task 2 and 3



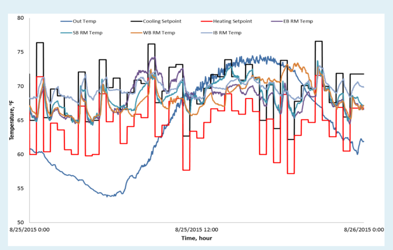

**Task 2 Develop and Calibrate an Online Building Energy Consumption Model**

**Task 2.1 Building Energy On-line Forecasting Through System Identification and Data Fusion**

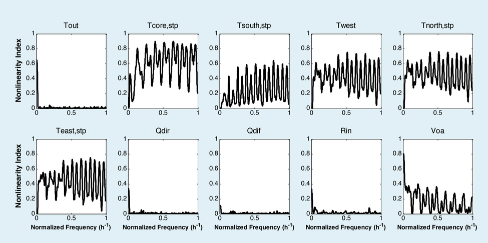
- Building energy system nonlinearity and response time test
  - Squared coherence magnitude test
- General methodology for building energy forecasting using system identification
  - Frequency response function
- Model comparison
  - Outperformed others
- Real building implementation
  - Iowa Energy Center
  - System characteristics test
  - System identification development and adaptation




Iowa Energy Center – small commercial building



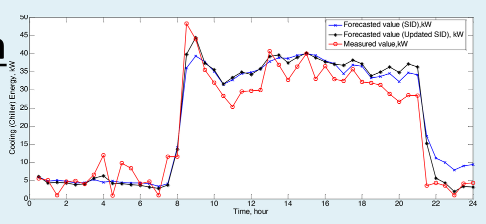
Real field measurement



System nonlinearity test

**Task 2.2 Building Energy Device Simulation Using Simplified Physics Models**

- Develop and validate simplified physics models for building energy device simulation against emulator results



Real field energy forecasting

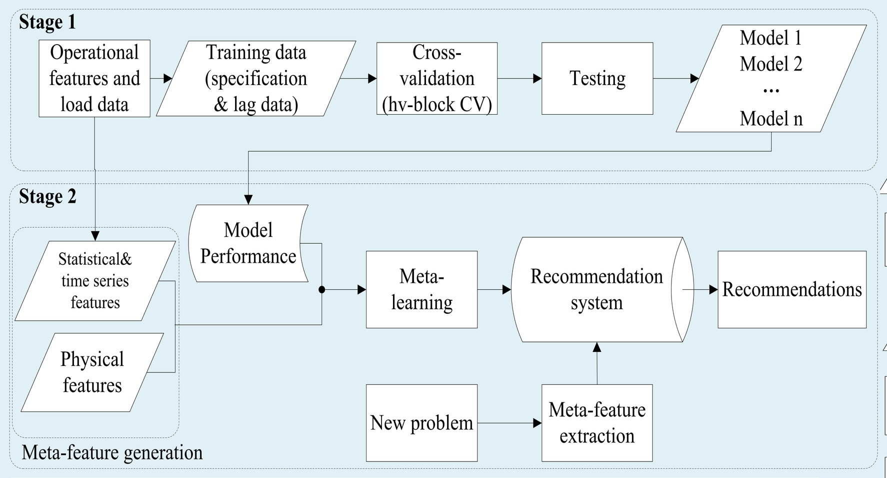
## Methods and Materials (ASU)

**Task 2 Develop and Calibrate an Online Building Energy Consumption Model**

- Develop accurate and robust energy forecasting models for building clusters
- The models are computationally efficient for real-time decision making

**Task 2.1 Building Energy Model Development: A Recommendation System**

- A meta-learning based recommendation system is proposed, which can select best models to forecast building energy profile for 48 DOE reference buildings of heterogeneous features

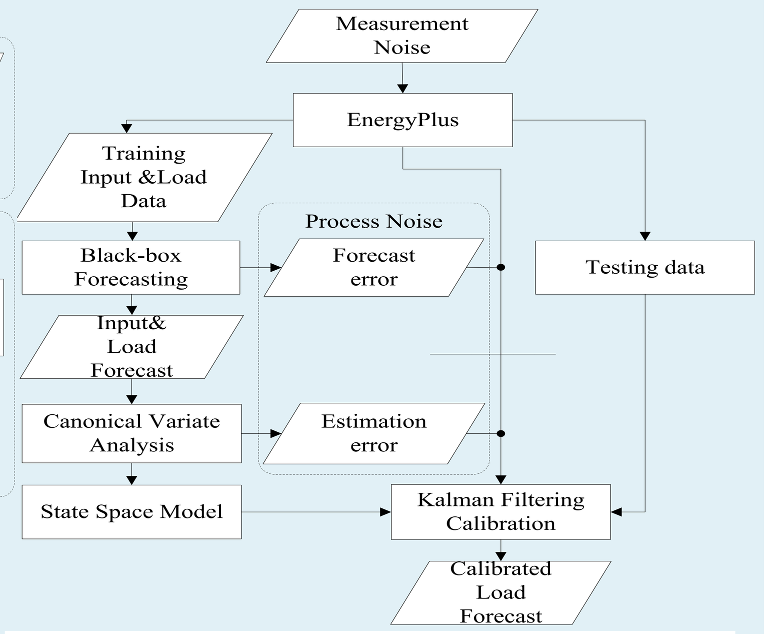


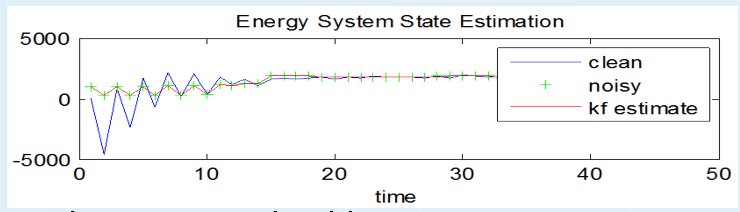

| | Building Energy Model Variables | Variable Type |
|---|---|---|
| 1 | Outdoor Air Drybulb Temperature (℃) | Continuous |
| 2 | Outdoor Air Relative Humidity | Continuous on [0,1] |
| 3 | Outdoor Air Flow Rate | Continuous |
| 4 | Diffuse Solar Radiation Rate (W/m²) | Continuous |
| 5 | Direct Solar Radiation Rate (W/m²) | Continuous |
| 6 | Zone People Occupant Count | Integer |
| 7 | Zone Air Temperature (℃) | Continuous |
| 8 | Zone Air Relative Humidity | Continuous on [0,1] |
| 9 | Zone Thermostat Cooling Setpoint Temperature (℃) | Continuous |
| 10 | Building Equipment Schedule Value | Continuous on [0,1] |
| 11 | Day of Week | Integer on [1,7] |
| 12 | Time of Day | Integer on [1,48] |

- The system is capable of automatically recommending the appropriate model(s) with accuracy of 90%
- Comparing to the traditional trial-and-error approach, meta-learning approach can achieve both of high prediction accuracy and high computational efficiency

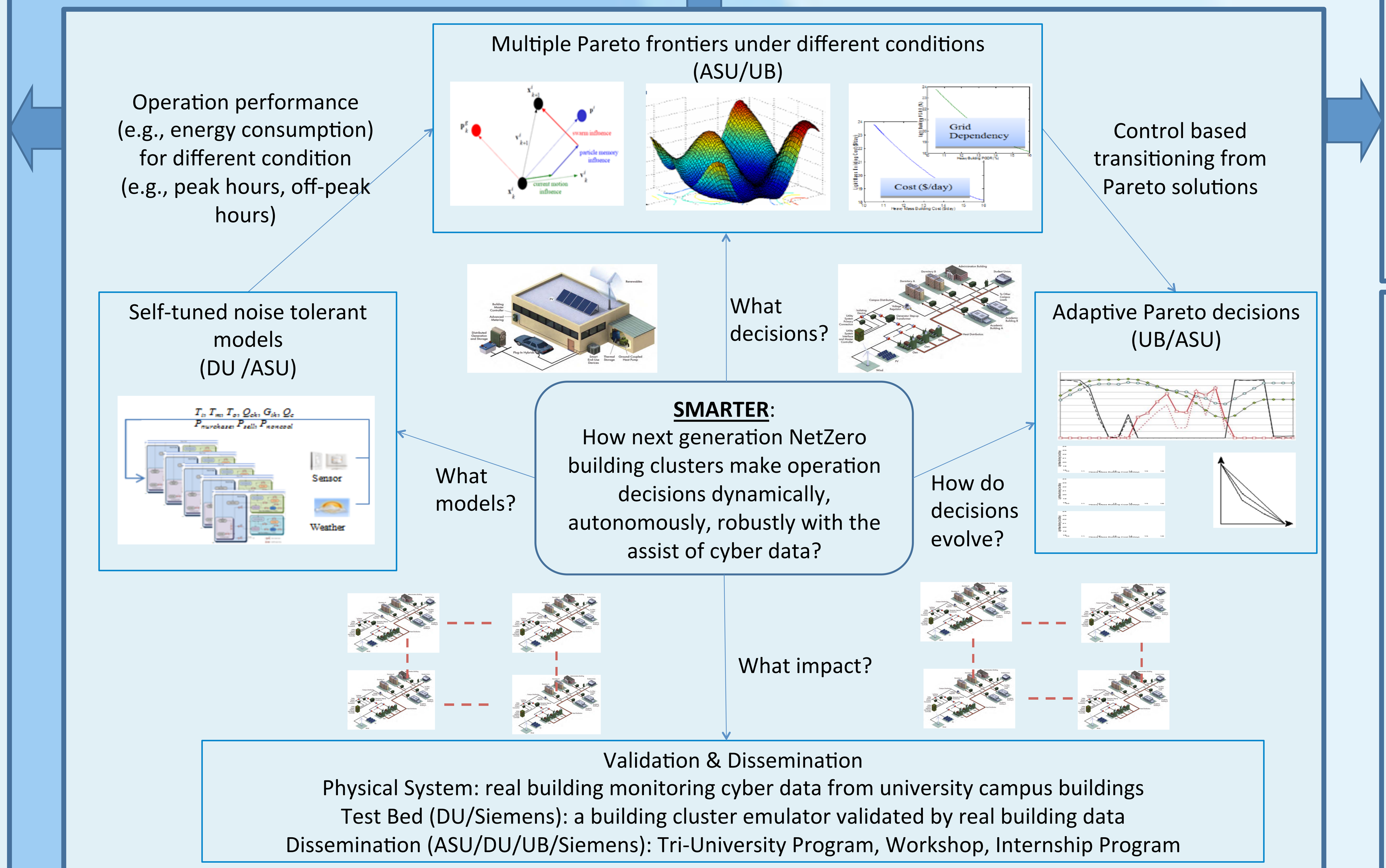
**Task 2.2 Calibrate an Online Building Energy Consumption Model**

- A Kalman filter assisted with canonical variate analysis (CVA) method is innovated to calibrate the recommended model




- The proposed calibration system gives more accurate forecasting result given noisy conditions and uncertainties




## Results

### 1. Swarm Intelligence Algorithm on Two Building Operation Decisions

Table 1 Daily Energy Cost ($/day)

| Solutions | | HMB ($/day) | LMB ($/day) | Total ($/day) |
|---|---|---|---|---|
| Pareto Decision (share energy & exchange information) | A | **4.97** | 9.96 | 14.93 |
| | B | 6.38 | **8.40** | 14.78 |
| | C | 5.19 | 9.05 | **14.24** |
| | D | 6.16 | 8.44 | 14.60 |
| | E | 5.55 | 8.88 | 14.43 |
| Case I | F | 5.13 | 10.07 | 15.20 |
| Case II | G | 6.93 | 8.89 | 15.82 |
| Case III | H | 5.05 | 10.59 | 15.64 |
| Case IV | I | 6.77 | 8.42 | 15.19 |

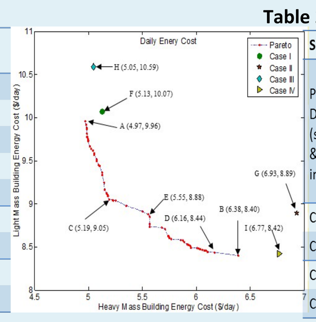
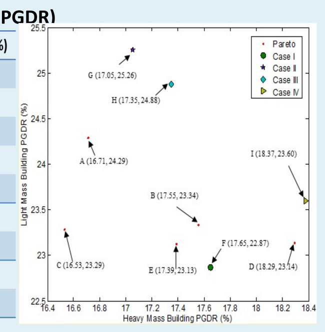



Table 2 Power Grid Dependency Rate (PGDR)

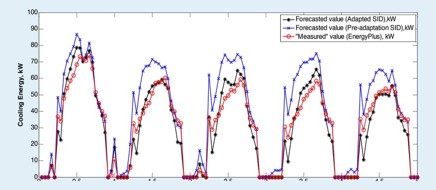
| Solutions | | HMB (%) | LMB (%) | Total (%) |
|---|---|---|---|---|
| Pareto Decision (share energy & exchange information) | A | 16.71 | 24.29 | 41.00 |
| | B | 17.55 | 23.34 | 40.89 |
| | C | **16.53** | 23.29 | **39.82** |
| | D | 18.29 | 23.14 | 41.43 |
| | E | 17.39 | 23.13 | 40.52 |
| Case I | F | 17.65 | **22.87** | 40.52 |
| Case II | G | 17.05 | 25.26 | 42.31 |
| Case III | H | 17.35 | 24.88 | 42.23 |
| Case IV | I | 18.37 | 23.60 | 41.97 |




### 2. Online Building Cluster Energy Model Results

- Cooling energy forecasting:
  - Accuracy: $R^2>0.9$
  - Speed: time<2 min

| Model | Excitation Interval | Excitation Frequency, $h^{-1}$ | Sample Length, h | $R^2$ | RMSE, kW | NRMSE |
|---|---|---|---|---|---|---|
| Small pre-adaptation | 30 min | 1-6 | 6 | 0.91 | 0.66 | 9% |
| **Small adapted** | **30 min** | **1-6** | **3** | **0.96** | **0.48** | **7%** |
| Medium pre-adaptation | 30 min | 1-6 | 6 | 0.73 | 12.15 | 16% |
| **Medium adapted** | **60 min** | **1-3** | **6** | **0.92** | **5.92** | **8%** |




Building energy forecasting

| Model | Linear/ Nonlinear | Excitation | Training Period | Testing Period | Calculation Time (s) | $R^2$ | RMSE | NRMSE |
|---|---|---|---|---|---|---|---|---|
| SID | L | Yes | 0801-0807 | 0822-0828 | 21 | **0.96** | **0.48 kW** | **7%** |
| N4SID | L | No | 0801-0814 | 0822-0828 | 2.88 | 0.89 | 1.11 kW | 15.6% |
| RC & Chiller | NL | No | 0801-0814 | 0822-0828 | 451 | 0.87 | 0.83 kW | 11.70% |
| SVR | NL | No | 0801-0814 | 0822-0828 | **0.02** | 0.69 | 1.04 kW | 14.59% |
| ANN | NL | No | 0801-0814 | 0822-0828 | 2.78 | 0.93 | 0.68 kW | 9.60% |

## Conclusions

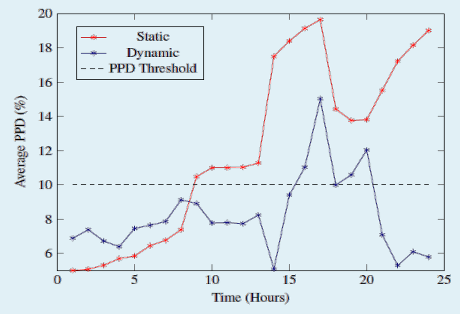
1. Grey box and black box models are complementary to each other for building energy consumption prediction. Grey box model shall be used for long term while black box model for short term prediction.
2. A Building Energy Model Recommendation is developed to effectively and efficiently identify the appropriate black box models for each building with its unique characteristics.
3. A decentralized decision framework has the potential to significantly reduce the energy cost. This framework is adaptive to the system dynamics (e.g., price, non-cooling load).

## Methods and Materials (UB)

**Task 3 Adaptive Decision Algorithms for Dynamic Operation Strategies**

**Task 3.1 Building energy consumption optimization framework**

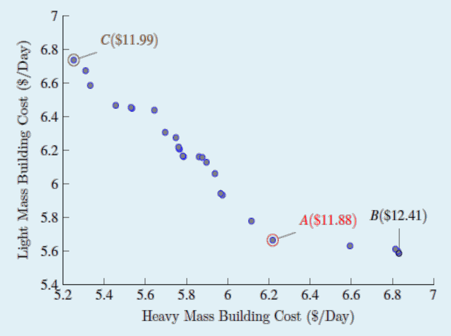
- Develop a bi-level NSGA-II driven optimization framework for building clusters
- Expand framework to allow for hourly energy optimization
- Visualize tradeoffs through Pareto analysis




*System response to dynamic preferences.*

**Task 3.2 Adaptive response to dynamic system inputs**

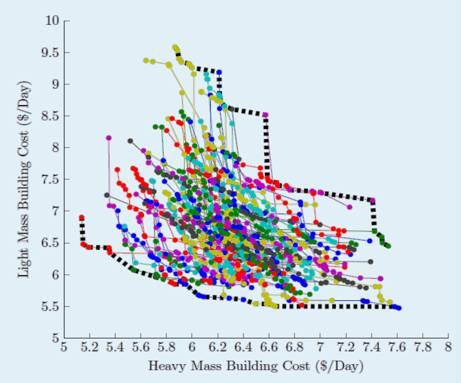
- Develop adaptive response for:
  - Dynamic energy pricing
  - Dynamic plug loads
  - Dynamic customer preferences




*Pareto frontier for cost-cost trade-off problem.*

**Task 3.3 Pareto Band exploration and frontier transitions**

- Develop Pareto band through Monte Carlo simulation and optimization
- Smoothly transition between frontiers to maintain optimality with respect to uncertainty




*Pareto band developed using Approach 2*

## Publications


1. Odonkor, P. and Lewis, K., 2015, "Adaptive Operation Decisions in Net Zero Building Clusters," ASME International Design Technical Conferences, Design Automation Conference, Boston, MA, DETC2015-47290.
2. Cui, C., Hu, M., Weir, J., Wu, T., "A Recommendation System for Meta-Modeling: A Meta-Learning Based Approach", Expert Systems and Application (in print), 2015.
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5. Chu, X., Hu, M., Wu, T., Weir, J.D., Lu, Q., "AHPS²: An optimizer using adaptive heterogeneous particle swarms", Information Sciences, vol. 280, pp. 26-52, 2014.
6. Hu, M., Weir, J., Wu, T., "An Augmented Multi-Objective Particle Swarm Optimizer for Building Cluster Operation", Applied Soft Computing (in print)
7. Li, X., Wen, J., Wu, T., 2014, "Net-Zero Energy Impact Building Clusters Emulator for Operation Strategies Assessment". ASHRAE 2014 Annual conference; Jun. 28 –Jul. 2, 2014, Seattle, WA, USA.
8. Li, X., Wen, J. 2014, "Building Energy Consumption On-line Forecasting Using System Identification and Data Fusion". ASME 2014 Dynamic Systems and Control (DSC) Conference, Oct. 22-24, 2014, San Antonio, TX, USA.
9. Hu, M., Wu, T., and Weir, J., 2013, "Multiobjective PSO for Building Cluster Operation Decisions," Industrial and Systems Engineering Research Conference, Puerto Rico.
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11. Cui, C., Wu, T, Hu, M., Weir, J.D., Chu, X., "Accuracy vs. Robustness: Bi-Criteria Optimized Ensemble of Metamodels", Winter Simulation Conference, 2014
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13. Hu, M., Wu, T., Weir, J.D., "An Adaptive Particle Swarm Optimization With Multiple Adaptive Methods," IEEE Transactions on Evolutionary Computation, vol.17, no.5, pp.705-720, 2013.