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Experiment Design and Training Data Quality of Inverse Model for Short-term Building Energy Forecasting

Liang ZHANG[1]*, Jin WEN[1], Can CUI[2], Xiwang LI[3], and Teresa WU[2]

[1]Drexel University, Department of Civil, Architectural and Environmental Engineering
[2]Arizona State University, School of Computing, Informatics, Decision Systems Engineering
[3]Harvard University, Graduate School of Design

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1
Introduction

1. Introduction

- To train black-box models for building energy forecasting, building data from normal operational lack sufficient information

- The focus of modeling has traditionally been on how to represent a data set well

However

- The impact of how such a data set represents the real system have not been well studied

- Mature excitation theories in system identification

However

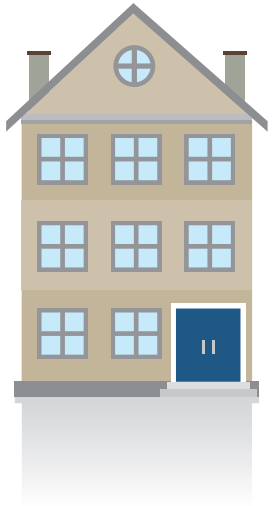
- Lack of universal theory for generating training training in black-box models

- Study whether excitation theories in system identification can be used in black-box model training process

1. Introduction

Building Physics ← Model to Represent Building Physics — Model ← Data to Train Model — Training Data

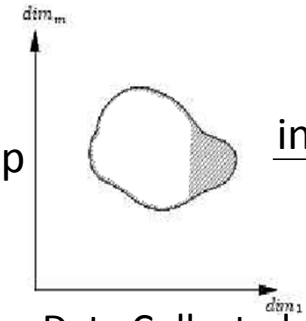
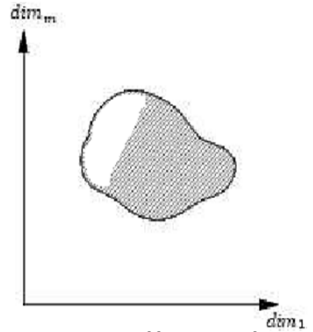
Short-term Building Energy Forecasting



m Disturbances**

n*inputs → **Model** for Building Energy → Energy output

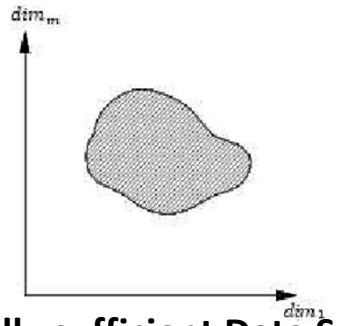
**Disturbances include outdoor air temperature, radiation, humidity, etc.
* Inputs include zone temperature set-point, occupancy schedule, ventilation rate, etc.

Develop  into 

Data Collected from **Normal Operation**

Data Collected from **Excitation**

By excitation or experiment design to be closer to the ideal data set for **Model**

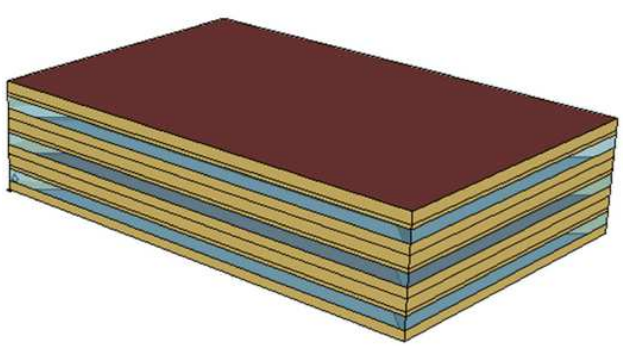


Ideally sufficient Data Set to Represent Model

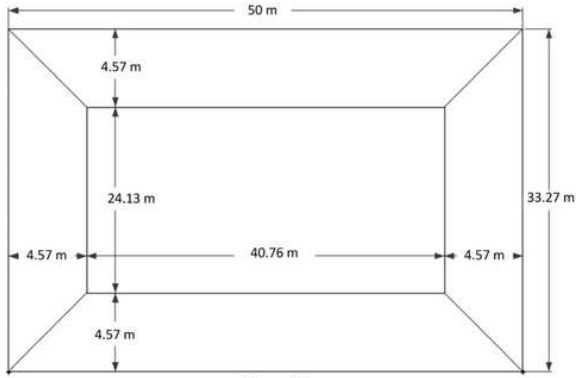
2
Experiment One: Normal Operation Data vs. Excitation Data

2. Experiment One: Normal operation data vs. excitation data

◈ **Experiment Building:** Virtual EnergyPlus Medium-size Reference Building



3D Building Model



Floor Plan

◈ **Normal Operation Description:**

- Zone temperature set-point schedule:

Week Days	Saturday	Sunday
Until: 06:00,26.7℃	Until: 06:00,26.7℃	Until: 24:00,26.7℃
Until: 22:00,24.0℃	Until: 18:00,24.0℃	
Until: 24:00,26.7℃	Until: 24:00,26.7℃	

2. Experiment One: Normal operation data vs. excitation data

◈ **Excite Object:** Zone Temperature Set-point

◈ **Excitation Details:**

- Signal: Multi-sine
- Frequency: 15 minutes
- Amplitude: [16,32]℃

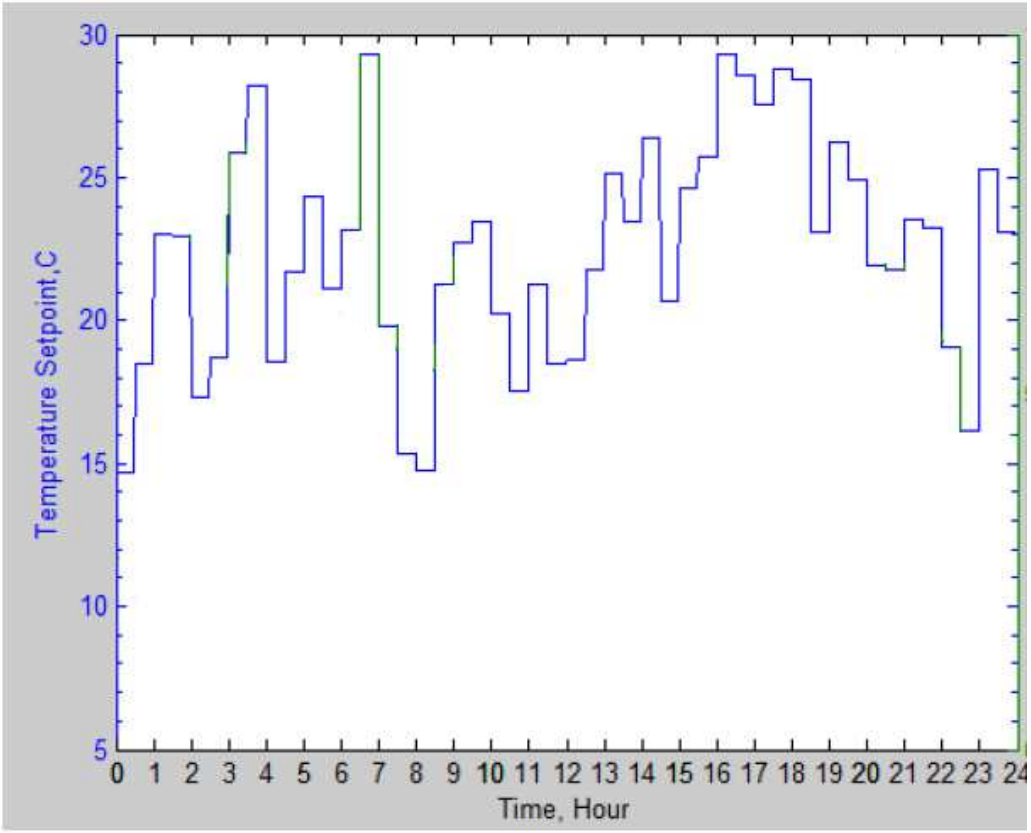
◈ **Black-box models:** Kriging, RBF, PR, MARS, SVM

(1 Excitation + 1 Normal Operation)

* 5 black-box models= 10 Models

◈ **Index to evaluate model accuracy and extendibility:**

- Normalized Root Mean Square Error (NRMSE) of
- Training error
- and testing error: similar weather condition (accuracy), extended weather condition (extendibility)



3
Experiment One
Results and Discussion

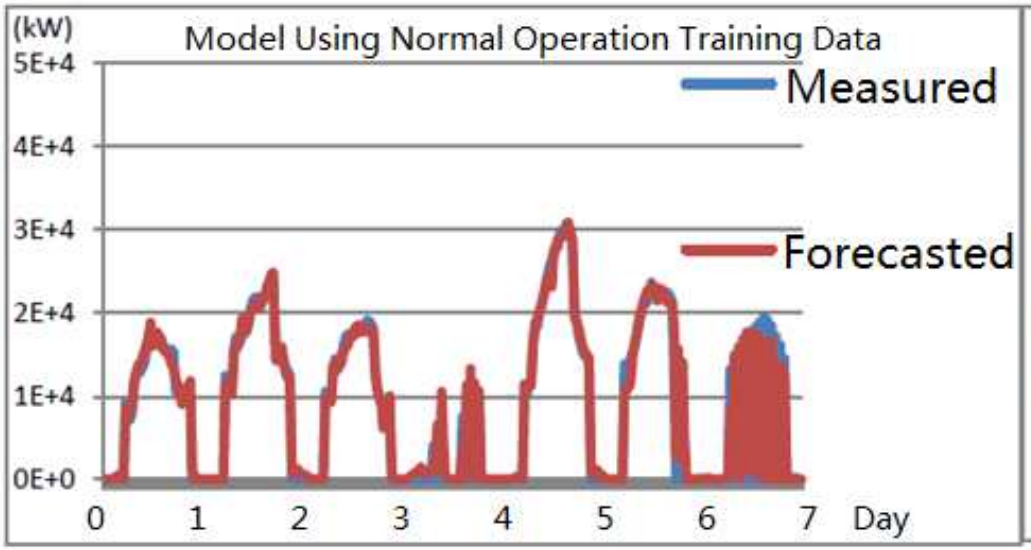
3. Experiment One Results and Discussion

Table 2: NRMSE of three testing of two models by seven algorithms

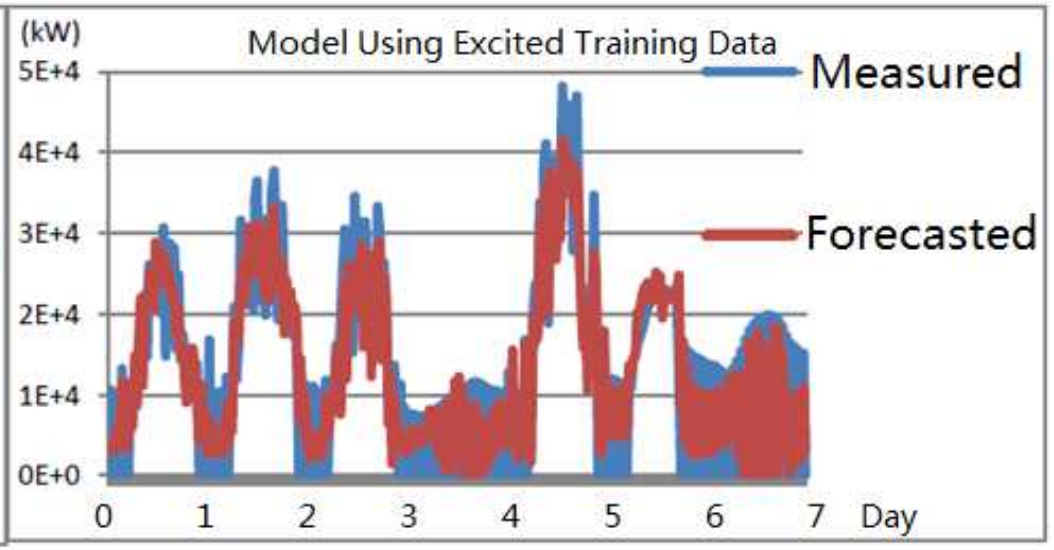
	NRMSE													
Algorithms	**SID[3]**		**Kriging**		**SVR**		**RBF**		**MARS**		**ANN**		**PR**	
Model	I[1]	II[2]	I	II	I	II	I	II	I	II	I	II	I	II
Testing using training data	0.203	0.147	0.000	0.000	0.163	0.180	0.000	0.000	0.039	0.066	0.036	0.083	0.071	0.099
Testing under similar weather	0.153	0.090	0.048	0.098	0.246	0.268	0.231	0.275	0.076	0.171	0.066	0.162	0.080	0.102
Testing under extended weather	0.160	0.089	0.074	0.090	0.250	0.259	0.189	0.199	0.119	0.175	0.092	0.159	0.085	0.093

1 Model I stands for models that trained with normal operation data
2 Model II stands for model that trained with excited operation data
3 SID stands for system identification method by frequency domain spectral density analysis

3. Experiment One Results and Discussion

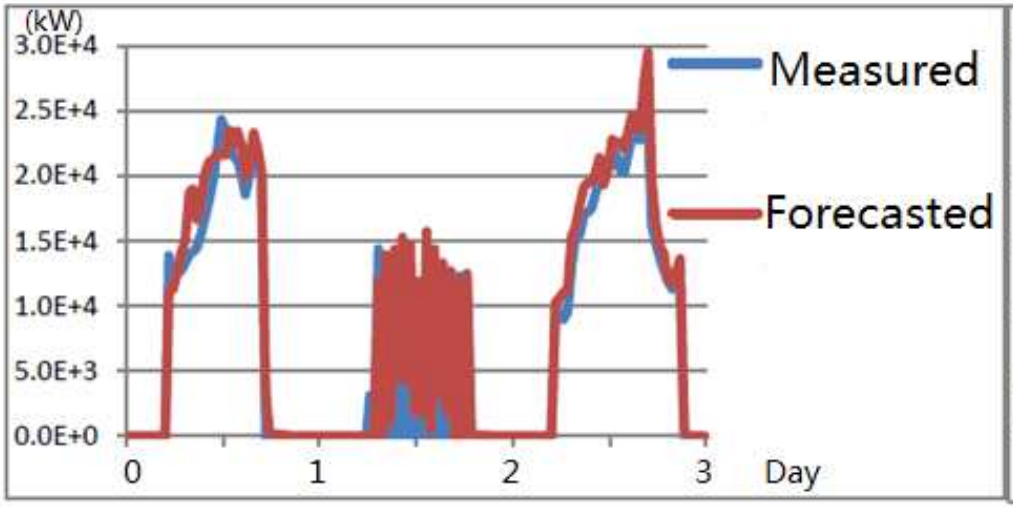


"Measured" vs. Ann model "Forcasted" using Normal Operation Training Data

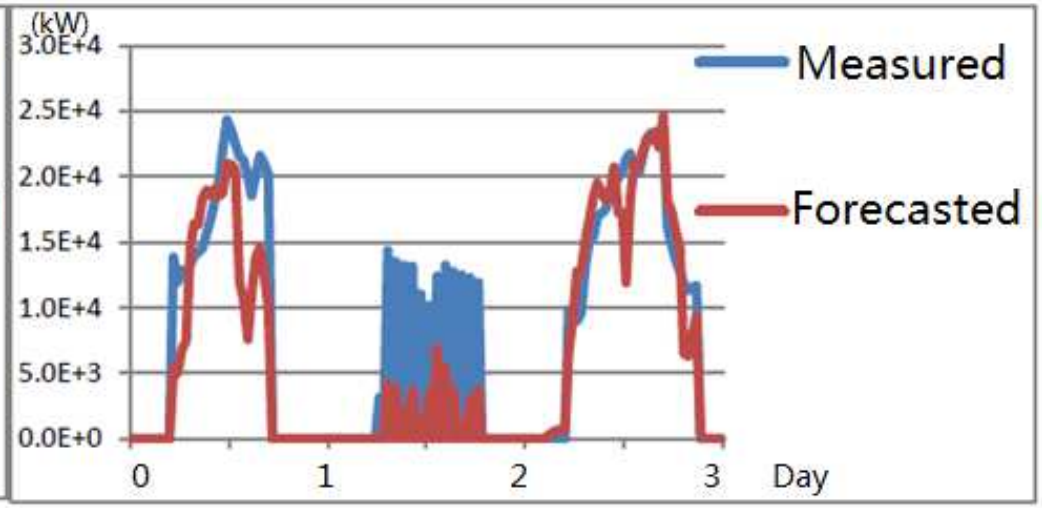


"Measured" vs. Ann model "Forecasted" using Excited Training Data

3. Experiment One Results and Discussion



"Measured" vs. ANN model "Forecasted"(Trained by Normal Operation Data) under test of similar weather condition



"Measured" vs. ANN model "Forecasted"(Trained by Excited Data) under test of similar weather condition

3. Experiment One Results and Discussion

By using normal operation training data to train models, most of the black-box models have higher prediction accuracy than System Identification (SID) model (17% better).

By using zone-temperate-excited training data to train models, the System Identification (SID) model has higher accuracy than most of the black-box models (48% better).

Training a System Identification (SID) model by using excited training data can raise the accuracy of forecasting (43% better).

However, for black-box models, training them by normal operation data can achieve better model accuracy than training them by excited inputs and output (32% worse).

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Experiment Two:
Different Excitation Schemes

4. Experiment Two: Different Excitation Schemes

- **Experiment Building:** Virtual EnergyPlus Medium-size Reference Building
- **Excite Object:** Zone Temperature Set-point
- **Excitation Details:**

- Signal: Pseudorandom Binary Signal (PRBS), Multi-level Pseudorandom Signal (MPRS), Multi-step Down Signal (MSDS)
- Frequency: 15min, 30min, 60min, 120min
- Amplitude: Small Range[24,26.7]℃, Medium Range[20, 30]℃; Large Range [16,32]℃

3 signal * 4 frequency * 3 amplitude = <u>36 excitation schemes</u>

4. Experiment Two: Different Excitation Schemes

◈ **Black-box modeling algorithms**: Kriging, RBF, PR, MARS, SVM

36 excitation * 5 black-box modeling algorithms = 180 Models

◈ **Index to evaluate model accuracy and extendibility:**

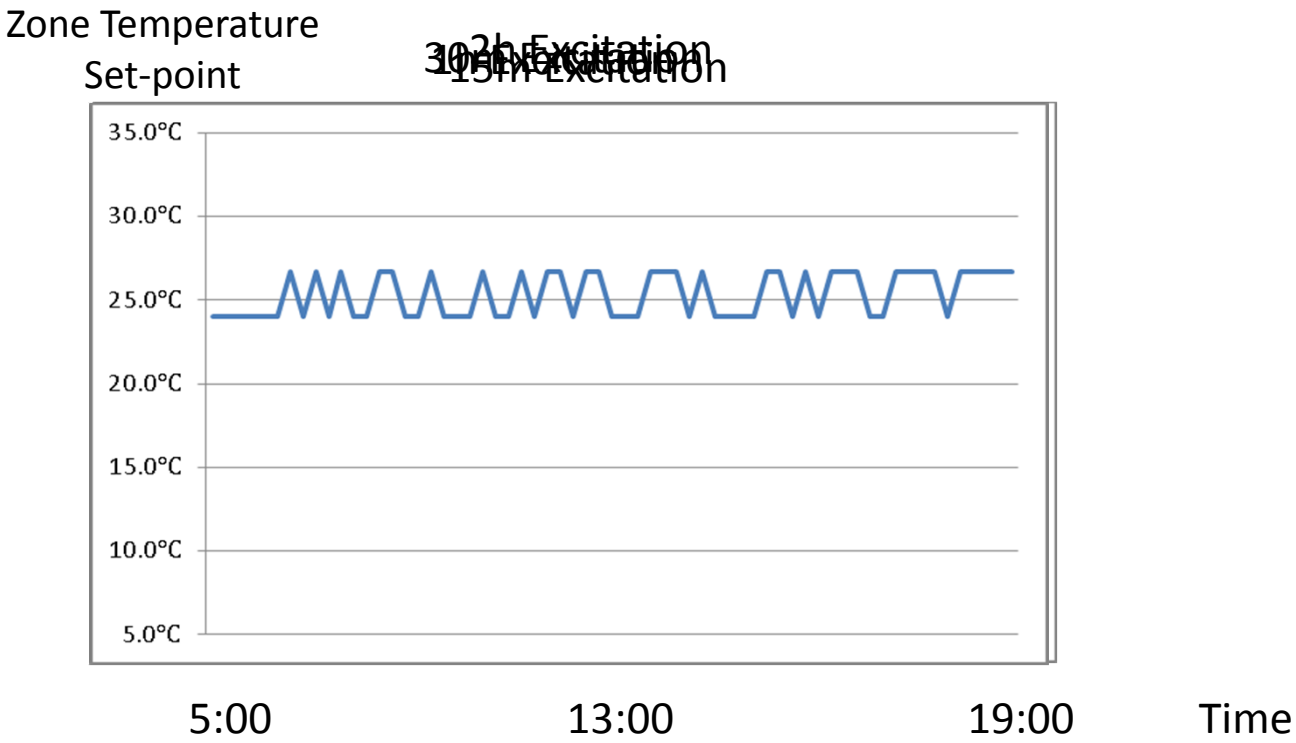
- Normalized Root Mean Square Error (NRMSE) of
- 1. Training error
- and Testing error: 2. similar weather condition (accuracy), 3. extended weather condition (extendibility), 4. extended zone set-point condition (extendibility)

180 Models * 4 kinds of training and testing error = 720 NRMSE to evaluate models and excitation effect

4. Experiment Two: Different excitation schemes

Zone Temperature Set-point Excitation Signal **Examples**

Pseudorandom Binary Signal (PRBS), Small Range: [24,26.7]℃



5
Experiment Two
Results and Discussion

NRMSE			Kriging				MARS				PR				SVM				RBF			
Normal			0.000	0.566	0.404	0.349	0.028	0.549	0.288	75.863	0.042	0.545	0.210	2.056	6.878	19.363	14.343	12.840	0.000	0.740	0.144	0.494
PRBS	Small Range	15min	0.000	0.748	0.479	0.462	0.041	0.092	0.107	157.203	0.055	1.047	0.877	1.125	8.526	32.294	22.548	21.502	0.000	0.983	0.230	0.641
		30min	0.000	0.788	0.829	0.471	0.041	0.147	0.250	323.603	0.050	0.976	0.690	1.337	2.586	10.666	7.193	7.072	0.000	0.961	0.300	0.624
		60min	0.000	0.689	0.464	0.430	0.036	0.117	0.117	258.835	0.055	0.869	0.629	1.984	0.206	0.717	0.280	0.486	0.000	0.882	0.285	0.574
		120min	0.000	0.636	0.447	0.394	0.046	0.096	0.103	4.749	0.041	0.828	0.523	1.938	33.654	128.667	90.459	85.819	0.000	0.845	0.240	0.547
	Medium Range	15min	0.000	3.770	2.526	2.456	0.039	0.391	0.301	0.887	0.087	3.633	2.601	2.514	101.529	0.471	0.470	0.446	0.000	2.803	1.377	2.083
		30min	0.000	2.955	1.905	1.919	0.038	0.472	0.359	0.277	0.075	2.592	2.576	2.336	43.686	0.471	0.470	0.446	0.000	2.450	1.444	1.595
		60min	0.000	2.808	1.860	1.823	0.041	0.481	0.385	0.714	0.071	2.805	2.[illegible]	2.042	4.889	0.471	0.470	0.446	0.000	1.960	1.091	1.266
		120min	0.000	1.714	1.307	1.148	0.038	0.447	0.371	0.502	0.042	3.069	2.155	2.051	253.700	2760.478	1959.175	1837.462	0.000	1.922	1.062	1.258
	Large Range	15min	0.000	4.914	3.908	3.434	0.027	1.318	1.221	1.070	0.082	11.316	8.360	7.811	0.355	10.841	6.532	7.201	0.000	6.140	3.581	4.496
		30min	0.000	5.781	4.503	3.812	0.033	1.597	1.450	1.791	0.068	11.788	9.[illegible]	8.015	102.880	0.471	0.470	0.446	0.000	5.040	2.376	3.367
		60min	0.000	5.050	4.100	3.321	0.026	1.522	1.279	1.766	0.064	12.238	8.925	8.250	184.291	0.471	0.470	0.446	0.000	5.266	3.558	3.497
		120min	0.000	4.636	3.602	3.139	0.029	1.598	1.376	1.312	0.040	13.813	10.[illegible]	[illegible]6.517	22803.260	16929.150	15281.560	0.000	3.928	2.340	2.596	
MPRS	Small Range	15min	0.000	0.737	0.472	0.459	0.041	0.115	0.132	0.175	0.054	1.056	0.904	1.335	11.918	8.505	15.414	10.365	0.000	0.949	0.199	0.569
		30min	0.000	0.939	0.382	0.585	0.040	0.142	0.198	0.203	0.052	0.927	0.713	1.136	5.858	21.367	14.735	14.210	0.000	0.754	0.252	0.479
		60min	0.000	0.595	0.434	0.359	0.036	0.118	0.128	0.250	0.053	1.147	1.249	1.[illegible]	19.682	26.347	43.577	27.430	0.000	0.868	0.278	0.552
		120min	0.000	0.689	0.387	0.414	0.033	0.142	0.311	0.309	0.037	1.052	0.926	1.309	1.820	7.235	5.246	4.775	0.000	0.865	0.385	0.544
	Medium Range	15min	0.000	1.107	0.718	0.667	0.039	0.372	0.314	1.859	0.075	2.335	1.589	1.603	1.553	0.471	0.470	0.446	0.000	2.607	1.426	1.687
		30min	0.000	1.875	1.425	1.267	0.038	0.415	0.402	2.042	0.069	1.914	1.498	1.359	12.049	0.471	0.470	0.446	0.000	2.036	1.528	1.404
		60min	0.000	1.536	1.040	1.055	0.031	0.423	0.302	32.765	0.069	2.352	1.759	1.656	20.304	228.787	158.386	151.869	0.000	2.079	1.557	1.360
		120min	0.000	1.324	1.073	0.878	0.034	0.538	0.434	0.852	0.048	1.555	1.159	1.033	0.320	0.471	0.470	0.446	0.000	1.893	1.315	1.235
	Large Range	15min	0.000	4.161	3.110	3.482	0.035	1.184	1.019	0.888	0.068	4.600	3.696	3.418	97.135	0.471	0.470	0.446	0.000	5.920	3.382	3.964
		30min	0.000	4.786	3.710	3.308	0.030	1.391	1.224	1.098	0.058	4.150	3.341	3.123	59.756	1433.420	1064.788	960.665	0.000	4.205	3.057	3.339
		60min	0.000	5.124	4.079	3.645	0.032	1.439	1.269	1.357	0.062	8.046	6.356	5.689	0.216	5.136	3.480	3.372	0.000	5.579	3.698	3.692
		120min	0.000	4.476	3.754	2.953	0.037	1.607	1.409	1.171	0.049	6.089	4.552	4.093	0.393	11.800	7.817	7.845	0.000	3.482	2.337	2.315
m-step-down	Small Range	15min	0.000	0.506	0.373	0.327	0.047	0.130	0.101	0.194	0.056	0.698	0.608	0.802	23.558	26.808	42.367	26.282	0.000	0.671	0.296	0.419
		30min	0.000	0.507	0.373	0.328	0.041	0.133	0.097	0.202	0.056	0.694	0.572	0.810	0.251	0.655	0.365	0.412	0.000	0.682	0.300	0.427
		60min	0.000	0.503	0.371	0.328	0.037	0.242	0.161	0.195	0.055	0.713	0.431	1.126	0.245	0.730	0.382	0.455	0.000	0.659	0.285	0.427
		120min	0.000	0.533	0.388	0.340	0.038	0.131	0.087	0.202	0.055	0.700	0.573	0.788	3.321	9.543	6.829	6.310	0.000	0.696	0.313	0.431
	Medium Range	15min	0.000	0.874	0.622	0.505	0.043	0.156	0.145	0.137	0.039	0.949	0.716	0.657	0.360	1.583	1.039	0.998	0.000	1.257	0.762	0.822
		30min	0.000	0.891	0.648	0.541	0.045	0.146	0.137	0.122	0.040	0.946	0.710	0.657	173.601	0.471	0.470	0.446	0.000	1.279	0.748	0.826
		60min	0.000	0.776	0.560	0.471	0.047	0.122	0.106	0.197	0.041	0.944	0.710	0.666	0.257	0.682	0.401	0.429	0.000	1.299	0.739	0.840
		120min	0.001	289.614	157.617	202.929	0.053	0.110	0.127	0.167	0.046	0.940	0.704	0.689	30.674	0.471	0.470	0.446	0.000	1.100	0.611	0.717
	Large Range	15min	0.000	1.863	1.361	1.239	0.064	0.507	0.518	0.314	0.028	1.732	1.313	1.126	0.424	1.903	1.400	1.208	0.000	2.449	1.783	1.608
		30min	0.000	2.112	1.590	1.354	0.063	0.499	0.504	0.309	0.029	1.695	1.278	1.102	0.329	1.362	1.007	0.853	0.000	2.334	1.701	1.514
		60min	0.000	1.976	1.491	1.269	0.053	0.501	0.456	0.286	0.032	1.750	1.279	1.138	32.800	0.471	0.470	0.446	0.000	2.305	1.613	1.497
		120min	0.002	77.690	35.263	51.608	0.060	0.408	0.427	0.246	0.036	1.784	1.279	1.168	18.431	139.027	94.656	92.330	0.000	2.179	1.622	1.400

Training Error Similar Weather Test Extended Weather Test Extended Set-point Test

5. Experiment Two Results and Discussion

M-level Step-down > MPRS > PRBS

Medium Range [20, 30] > Small Range[24,26.7] > Large Range[16,32]

30min = 60min > 15min >> 120min

MARS > RBF > Kriging > PR > SVM

6
Conclusions

6. Conclusions

- Excitation can effectively improve accuracy of System Identification models. But may not effectively improve Black-Box models' accuracy
- In most cases, excitation can increase extendibility of black-box models, but only occasionally increase model accuracy
- For each Black-Box model, there exists a specific excitation scheme that can improve the accuracy more than other schemes
- When excitation frequency is too high or too low, or when excitation signal amplitude is too large or too small, using excitation data will not improve model accuracy
- Excitation algorithm matters: M-level Step-down>MPRS>PRBS

7
Future Work

7. Future Work

Extend the present research in terms of:

- Building size
  - Small size
  - Medium size
  - Large size
- Excitation Objects
  - Zone temperature set-point
  - Supply air temperature set-point
  - Chiller set-point

Thanks!

ANY QUESTIONS?

You can find me at:
lz356@drexel.edu