ESL-IC-13-10-12a

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CALIBRATION OF PREDICTED HOURLY ZONE-LEVEL SUPPLY AIR FLOWS WITH MEASUREMENTS

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ICEBO

Université Concordia University

Calibrated building energy models

CALIBRATION = successively changing the inputs and parameters in order to reach good agreement between predictions and measurements

Results depend greatly on a number of factors:

- User's experience with energy simulation programs
- Time allocated for the calibration
- Knowledge of design and operation of the building and HVAC systems

Calibrated building energy models

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Current CALIBRATION approaches:

- Trial and error (*Troncoso 1997*);
- Optimization (*Reddy 2006; Millette at al. 2011*);
- Evidence-based (*Raferty 2009, 2011; Bertagnolio et al. 2012*).

Bottom-up calibration at system/component level

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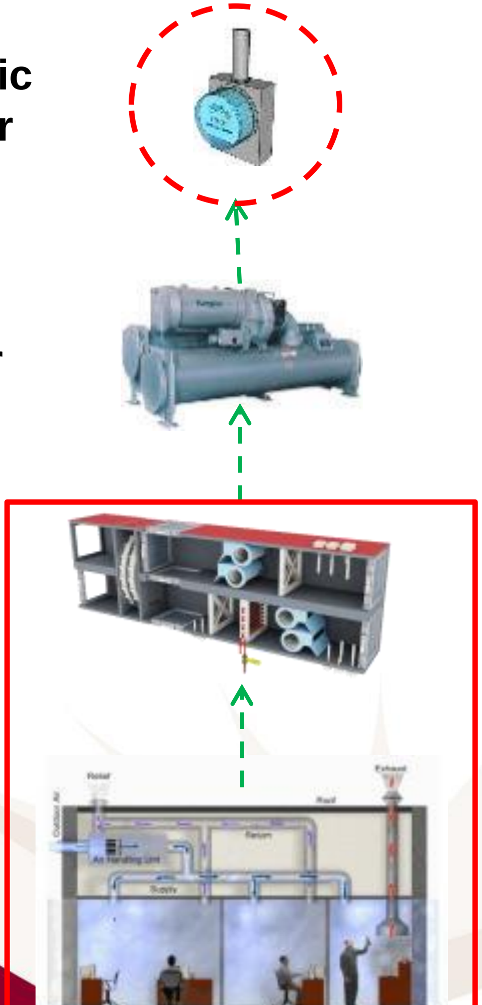

Parameters that can be calibrated:

Electric meter

Calibration of ENERGY USE
- With monthly utility bills

- ➢ Energy use NOT ONLY!

Chiller

Calibration of PRIMARY HVAC systems
- Chillers
- Boilers
- Cooling towers

- ➢ Energy use
- ➢ Liquid flow rate
- ➢ Liquid temperature
- ➢ COP

AHU

Calibration of SECONDARY HVAC systems
- Air handling unit
- Air or liquid distribution systems

- ➢ Air flow rate
- ➢ Temperature of air
- ➢ Humidity ratio

Zones

Calibration of ZONES

- ➢ Air temperature
- ➢ Supply air flow rate
- ➢ Cooling / heating load

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Methodology

1. Selection of measurement points available in the EMS and transfer to user's database

2. Verification of data quality and treatment

3. Data mining

4. Development of initial building model

5. Calibration of supplied air flow rate to each zone and indoor temperature

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Methodology

6. Calibration at the air handling unit (AHU)
   - for supply air flow rate and temperature
   - for the thermal loads of the cooling/heating coil
   - for the fan electric input
7. Calibration at the chilled/hot water loop level
8. Whole building model calibration

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Case study

Figure 1 Research Centre for Structural and Functional Genomics

Research Center for Structural and Functional Genomics of Concordia University

- Built in 2011
- Total floor area – 2000 m^2
- Three floors above ground
- 48 offices, conference rooms and laboratories
- Two VAV handling units in parallel

Measurements every 15 minutes from June 1^{st} to August 30^{th} 2012

Energy model

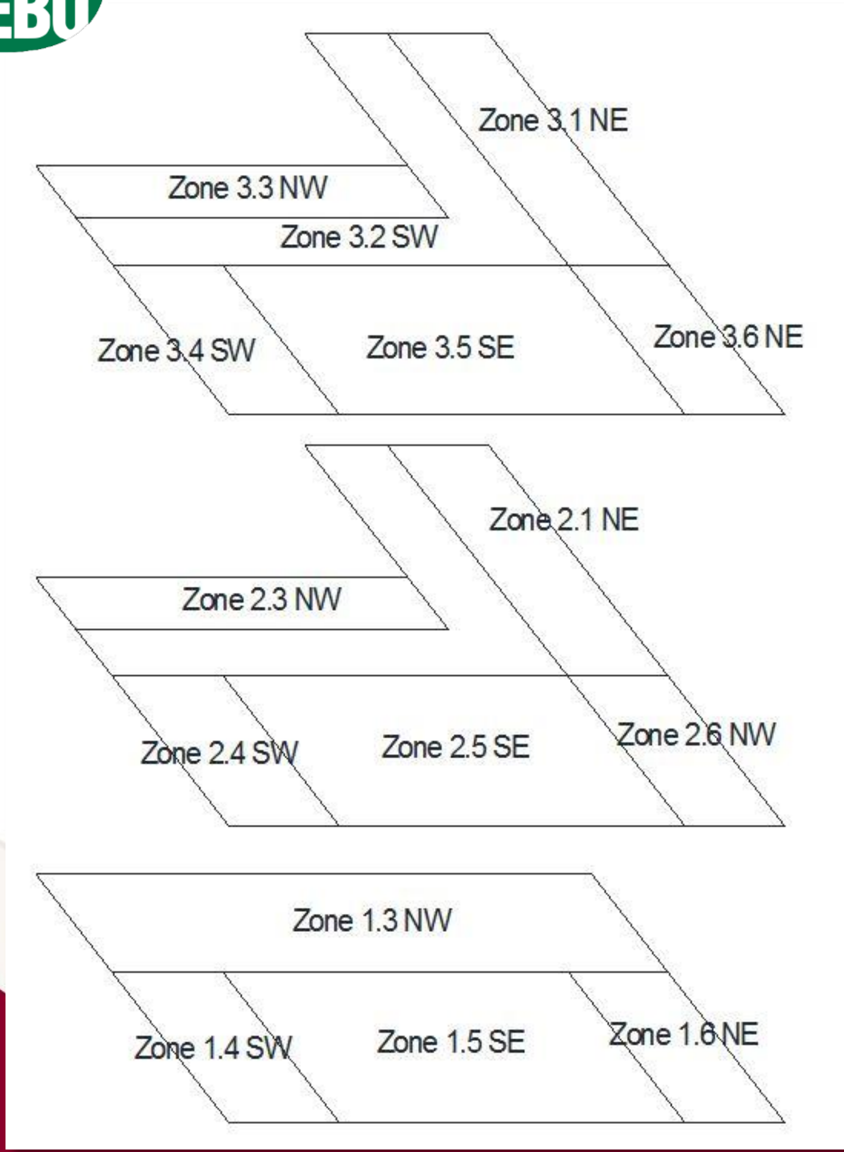

Figure 2 Zoning

- eQuest (the Quick Energy Simulation Tool)
- Fifteen thermal zones defined (based on orientation & occupancy)
- Exported **HOURLY** values of some selected variables

Evidence-based calibration

Changes to THERMOSTAT SET-POINT

- Specifications: thermostat set-point = 23.2 ºC
- Measurements: Indoor air temperature differs from one zone to the other for weekdays and weekend days.

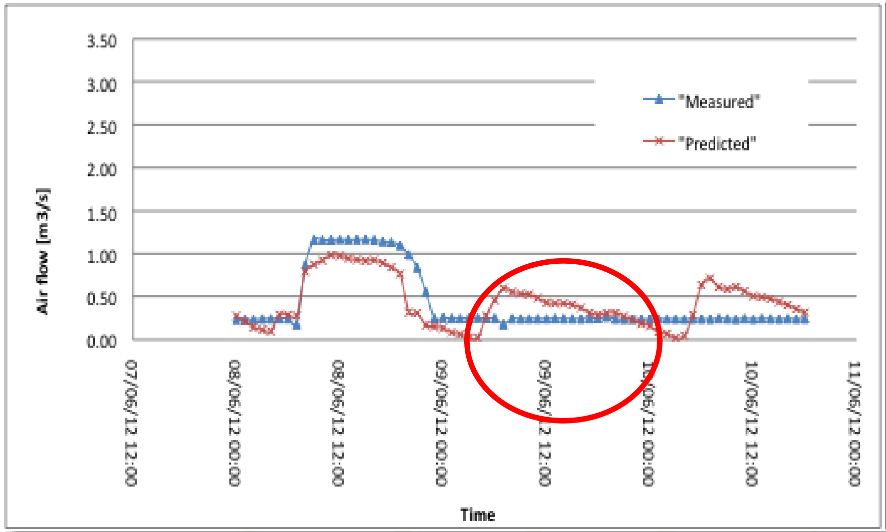

Figure 3 Measured vs. predicted hourly supply airflow rate in zone 1.6NE over three days in June 2012, with constant set point temperature of 23.9° C

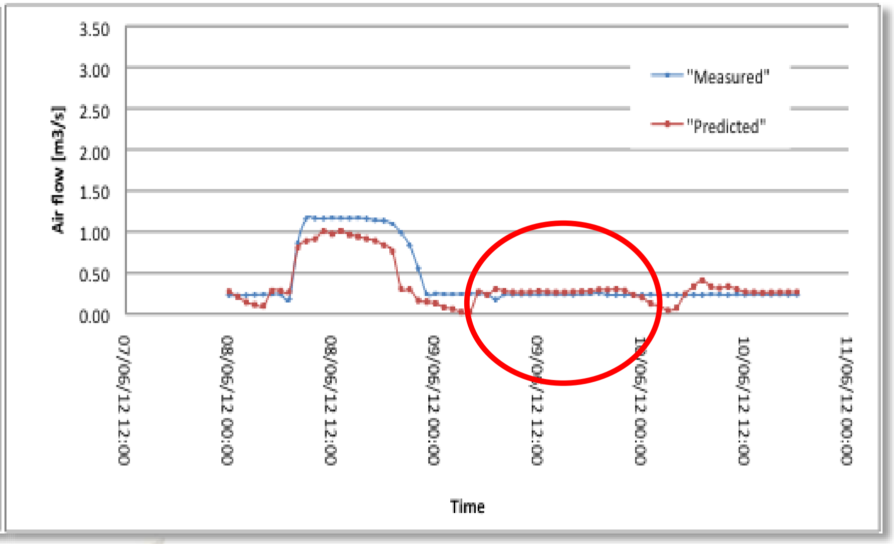

Figure 4 Measured vs. predicted hourly supply airflow rate in zone 1.6NE over three days in June 2012, with thermostat setup during unoccupied hours (26.1° C)

Evidence-based calibration

Rectangular-shape daily schedules

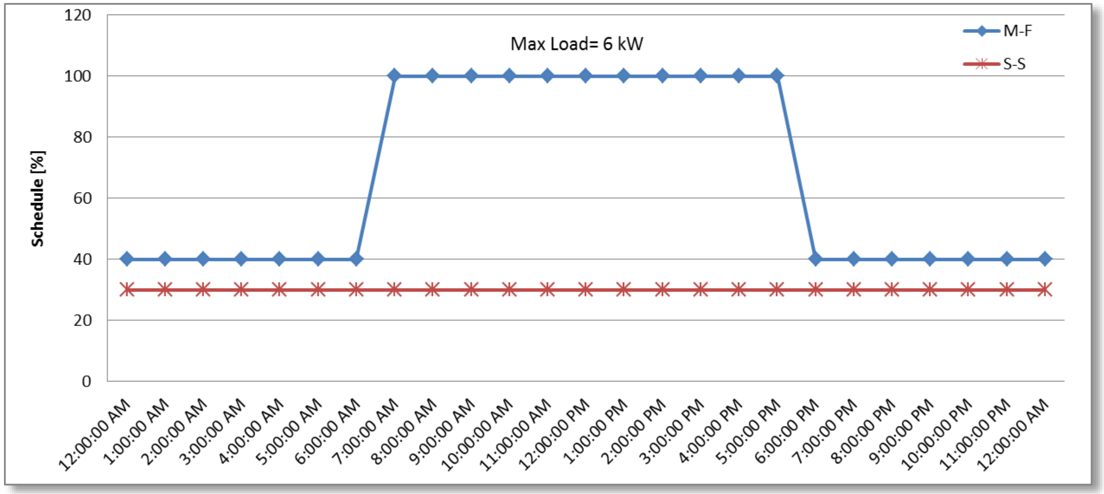

Figure 5 Equivalent rectangular-shape daily schedule for zone 1.3 NW

Maximum/ Minimum supply airflow rate

ZONE	MEASURED AIRFLOW RATE [m³/s]		DESIGN AIRFLOW RATE [m³/s]		DESIGN MIN AIRFLOW RATE	MEASURED MIN AIRFLOW RATE
	Occ.	Unocc.	10 ACH	3 ACH	%	%
1.4SW	0.82	0.01	1.02	0.31	30	2
1.6NE	1.26	0.22	1.02	0.31		17
3.5SE	2.76	1.65	4.52	1.35		67

Table 1
Measured vs. design daily average airflow rate

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Evidence-based calibration

Blinds

Shading and side fins

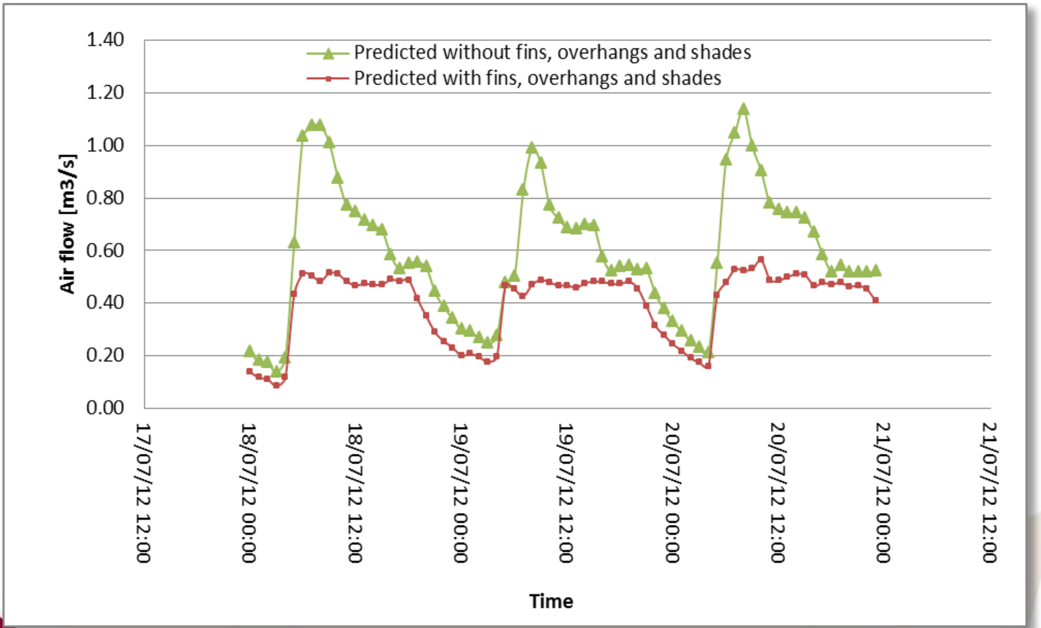

Figure 6 Blinds and side fins of the Genomics research center

Figure 7 Measured vs. predicted airflow rates for zone 1.6NE, without and with fins and building shades, for three days in July 2012.

Evidence-based calibration

Weather data

- Weather file obtained from Weather Analytics based on measurements at Montreal International Airport;
- Year 2012 was a leap year.

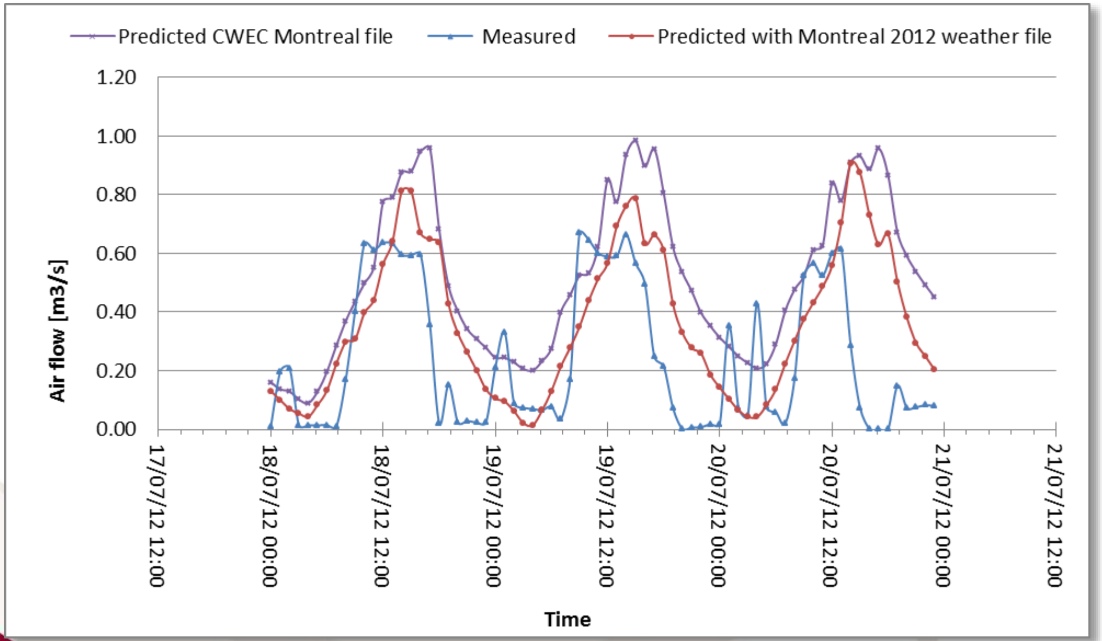

Figure 8 Measured vs. predicted airflow rate for zone 1.4SW with CWEC and Montreal 2012 weather files, for three days in July 2012.

Evidence-based calibration

Daylight savings time

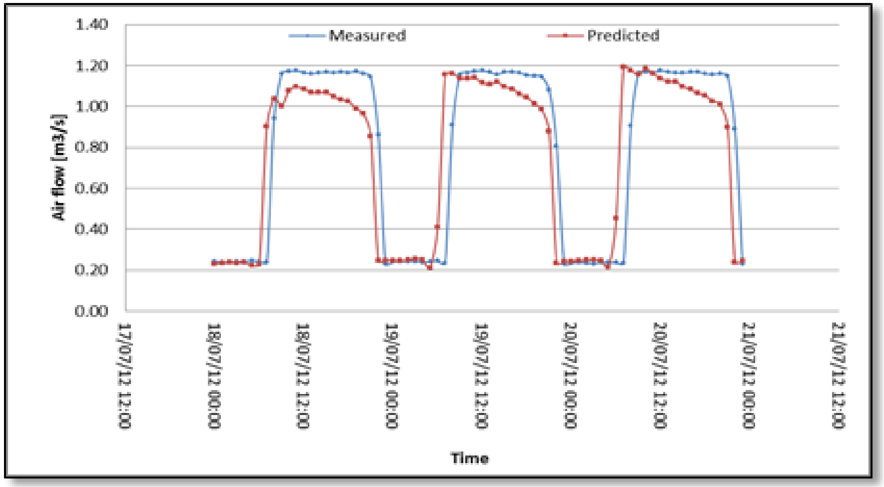

Figure 9 Measured and predicted air flow rate for zone 1.6 NE, for three days in July 2012 with the greatest outdoor air temperature recorded before the adjustment of daylight savings time

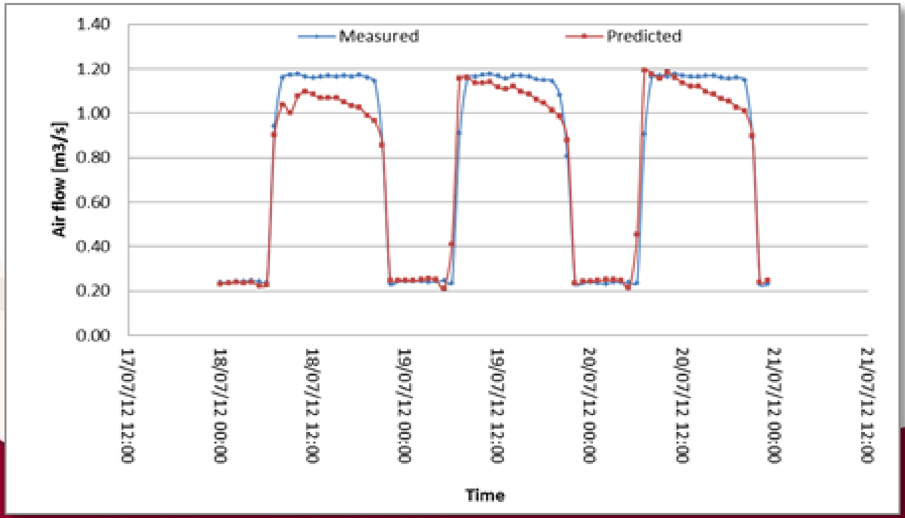

Figure 10 Measured and predicted air flow rate for zone 1.6 NE, for three days in July 2012 with the greatest outdoor air temperature recorded after the adjustment of daylight savings time

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Evaluation of the calibration quality

Three methods are proposed for comparing the measured data with the predictions:

1. Graphical representation
2. Statistical indices (RMSE, CV-RMSE and NMBE)
3. Statistical hypothesis testing

Graphical representation

Based on standard hourly time-series comparison

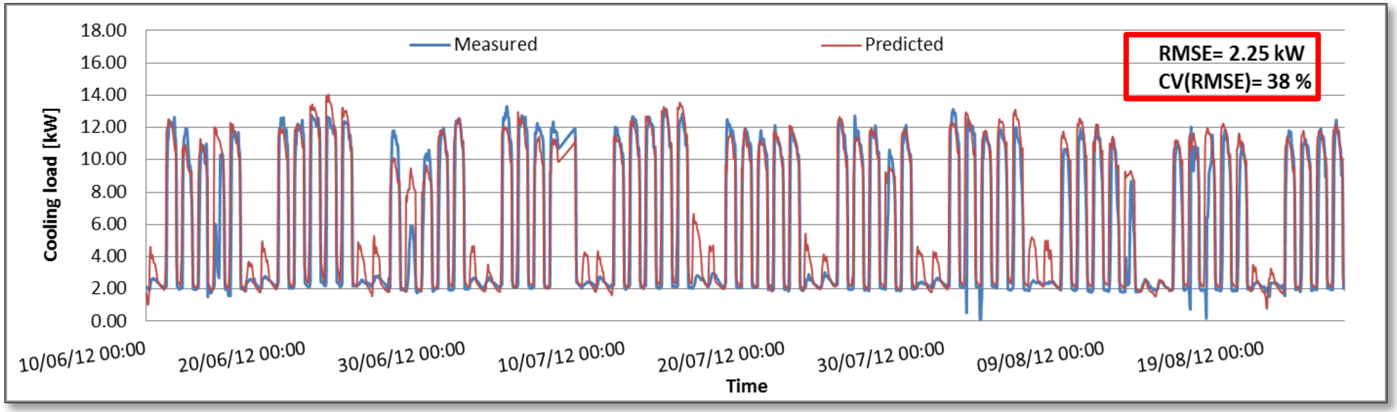

Figure 11 Measured vs. predicted cooling load for zone 1.6 NE

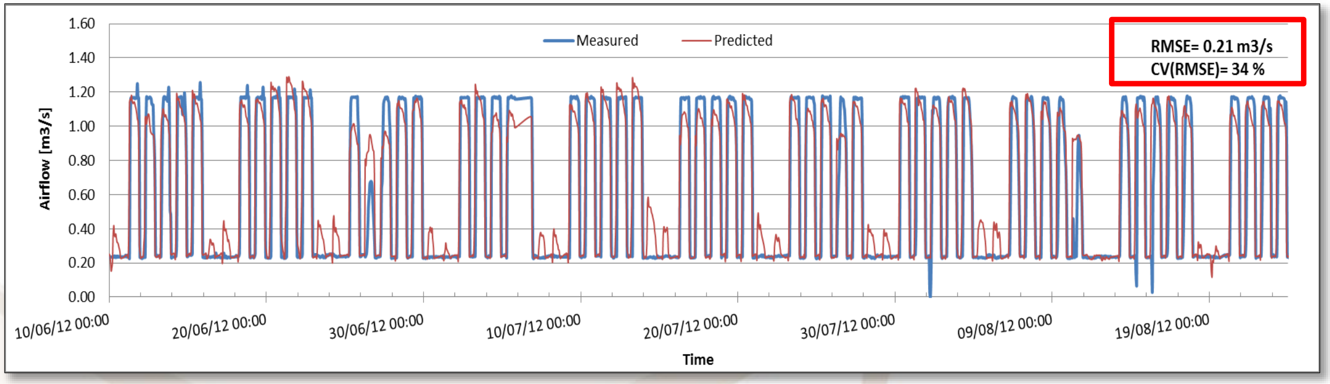

Figure 12 Measured vs. predicted air flow rate for zone 1.6 NE

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Statistical indices

RMSE – estimates the magnitude of error in the model

ASHRAE Guideline 14 requires using two different statistical indices to comply with the "Whole Building Calibration Path": CV-RMSE and NMBE:

CV-RMSE – normalized dimensionless quantity that measures the relative error between measured and predicted values

NMBE – represents the difference between measurements and predictions, related to the mean value

Statistical indices

Prescriptions for whole building energy use:

		CV-RMSE [%]	NMBE [%]
ASHRAE Guideline 14 and Federal Energy Management Program (FEMP)	Hourly	30	10
	Monthly	15	5
International Performance Measurement & Verification Protocol	Hourly	20	-
	Monthly	5	-

CV-RMSE [%]

CV-RMSE [%]				
Zone	Summer			Hourly over three days
	Hourly	Daily	Monthly	
1.3 NW	38.6	35.7	34.6	41.5
1.4 SW	103.4	40.5	19.0	88.6
1.5 SE	11.6	6.5	3.0	13.4
1.6 NE	20.1	10.8	6.3	30.3
2.1 NE	18.8	9.5	4.2	24.2
2.3 NW	93.5	49.1	23.0	60.9

Table 2
Coefficient of variation of the root mean squared error of the difference between measured and predicted air flow rate

NMBE [%]

NMBE [%]				
Zone	Summer			Hourly over three days
	Hourly	Daily	Monthly	
1.3 NW	34.57	34.91	51.85	37.96
1.4 SW	20.97	21.09	28.36	17.49
1.5 SE	-2.31	-2.26	-1.86	-1.72
1.6 NE	-2.43	-2.17	-6.78	3.81
2.1 NE	3.49	3.85	6.07	9.83
2.3 NW	7.02	7.36	9.66	1.93

Table 3
Normalized mean biased error of the difference between measured and predicted air flow rate

Statistical hypothesis testing

Null hypothesis H_0: abs(M - P) $\leq$ u

Alternative hypothesis H_1: abs(M - P) > u

Critical t value $t_{critical} = f(\alpha, df)$

If $t < t_{critical}$ then H_0 is TRUE

M= measured air flow rate [m³/s] or [cfm];
P= predicted air flow rate [m³/s] or [cfm];
u= uncertainty of measuring air flow rate [m³/s] or [cfm].

Statistical hypothesis testing Normal Distribution

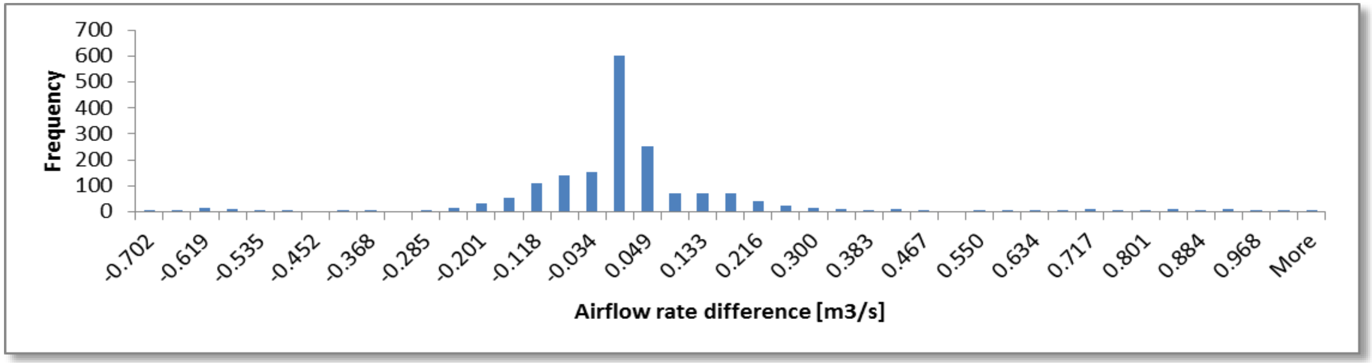

Figure 13 Histogram for the difference between measured and predicted air flow rate for zone 1.6 NE

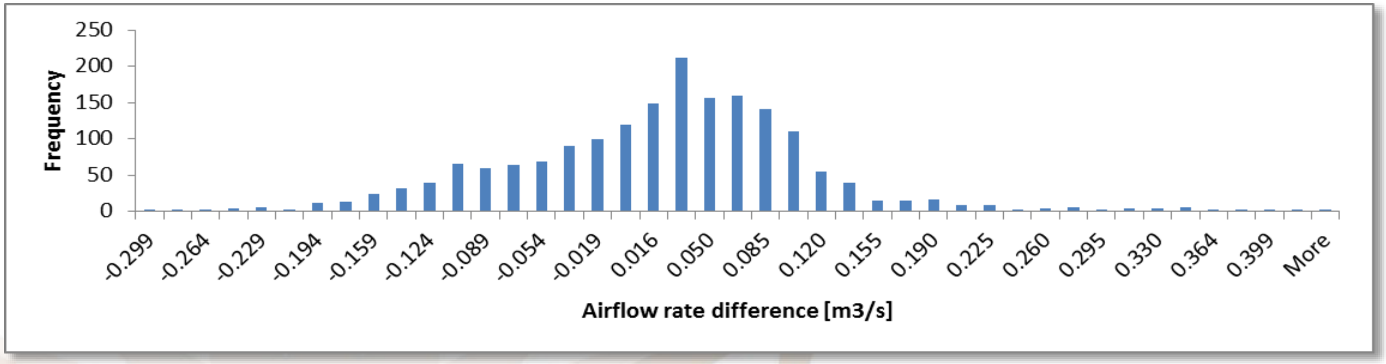

Figure 14 Histogram for the difference between measured and predicted air flow rate for zone 3.1 NE

Statistical hypothesis testing

CV-RMSE (hourly) [%]		
Zone	$t < t_{critical}$	$t > t_{critical}$
1.3 NW		38.6
1.4 SW		103.4
1.5 SE	11.6	
1.6 NE	**20.1**	
2.1 NE		18.8
2.3 NW	**93.5**	
2.4 SW		28.4
2.5 SE		11.1
2.6 NE		17.1
3.1 NE	19.4	
3.2 SW		20.9
3.3 NW		55.1
3.4 SW		26.9
3.5 SE	8.5	
3.6 NE		18.6

Table 4
Hourly coefficient of variation for all zones in the building for the summer period

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Statistical hypothesis testing

CV-RMSE (hourly) [%]		
Zone	t < $t_{critical}$	t > $t_{critical}$
2.5 SE		11.1

Table 5
Hourly coefficient of variation for zone 2.5 SE for the summer period

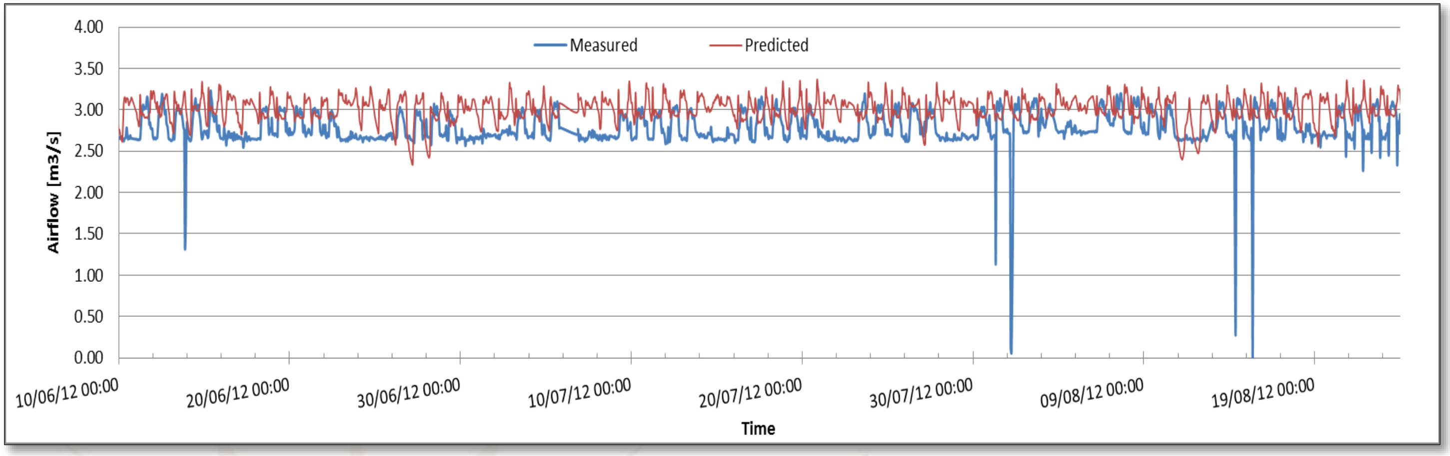

Figure 15 Predicted vs. measured air flow rate for zone 2.5 SE, for the entire summer

Statistical hypothesis testing

CV-RMSE [%]				
Zone	Interval	Time step	t < t,cr	t > t,cr
2.1 NE	Summer	Hourly		18.8
		Daily	9.5	
		Monthly		4.2
	3 days	Hourly	24.2	
2.4 SW	Summer	Hourly		28.4
		Daily	12.7	
		Monthly	4.0	
	3 days	Hourly	29.7	
2.6 NE	Summer	Hourly		17.1
		Daily		11.7
		Monthly		8.9
	3 days	Hourly	16.5	
3.2 SW	Summer	Hourly		20.9

Table 6
Comparison between the hourly, daily and monthly calibration analysis: CV-RMSE[%] vs. t-test

Conclusion

- Developed a bottom-up approach that uses measured data as much as possible
- Comparison of measurements with predictions performed with:
  - Graphical representation
  - Statistical indices:
  - Paired difference hypothesis testing
- Graphical representation and statistical indices approach not sufficient

- **Must be accompanied by a paired difference hypothesis testing!**

Future work

- Data mining and automatic export of information to the input file;
- Calibration of swing and heating seasons;
- Calibration of water-side loop of HVAC system and energy use;
- Whole-building energy use calibration;
- Analysis of a set of three days other than the ones that present the highest outdoor temperature;
- Use of schedules from ASHRAE RP-1093 Diversity Factor Toolkit (Claridge et al.2004).

Thank you !

Questions ?