Improving Data Center Energy Efficiency through End-to-End Cooling Modeling and Optimization

University of Colorado Boulder

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Project Summary

Timeline:

Start Date: 10/1/2016
Planned end date: 11/30/2019

Key Milestones

- Optimization of Cooling System Operation; 12/31/17
- Optimization of Airflow Management System; 11/30/18
- Simultaneous Optimization of Airflow Management and Cooling Systems; 8/31/19

Budget:

Total Project $ to Date:

- DOE: $87,141 (9/16-8/17)
- Cost Share: $28,279 (9/16-8/17)

Total Project $:

- DOE: $522,460
- Cost Share: $92,185

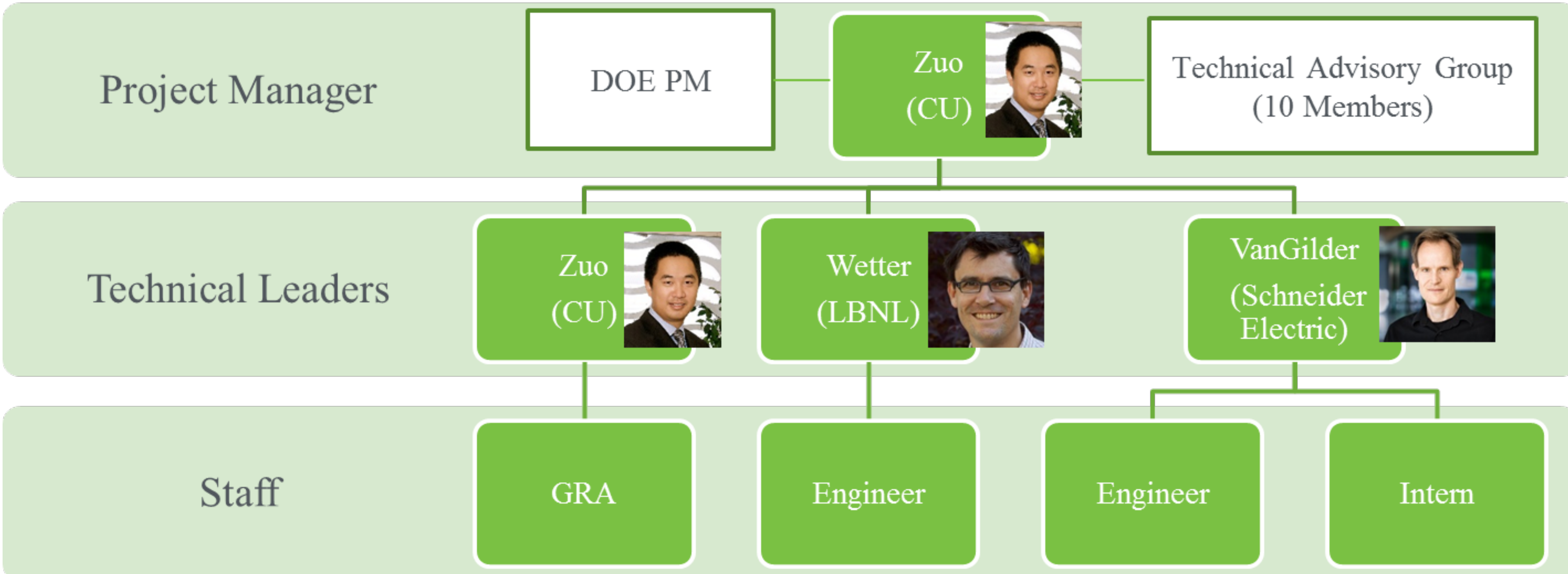
Key Partners:

University of Colorado Boulder
Lawrence Berkeley National Laboratory
Schneider Electric
University of Miami
University of Massachusetts Medical School

Project Outcome:

- A holistic data center cooling system modeling and optimization software at Technical Readiness Level (TRL) 7.
- Demonstrated 30% energy savings at two data centers in Massachusetts and Florida.

Team



- **Wangda Zuo**: *Associate Professor and Lewis-Worcester Faculty Fellow at University of Colorado Boulder,* expert in building energy efficiency[1], energy modeling[2] and indoor airflow simulation[3,4].
- **Michael Wetter**: *Staff Scientist at Lawrence Berkeley National Laboratory*, primary author of Modelica Buildings library[5], BCVTB[6], and GenOpt[7].
- **Jim VanGilder**: *PE, Director of Thermal Analytics at Schneider El*ectric, 20+ patents and dozens of papers on data center cooling[8-10].

Challenge

Problem Definition:

- Data centers in the US use about 2% electricity of the nation and half of this is used for cooling[11]. The estimated electricity usage for data center cooling will be about 70 billion kWh in 2020.
- Current data center modeling programs focus on either data center room airflow management or cooling system simulation, with models designed only for limited, specific applications.

Solutions:

- Develop first practical tool that **couples the modeling of airflow-management and cooling systems to enable a global data center cooling optimization.**
- The tool will have three unique features:
  1. Optimization of cooling system operation enabled by Modelica models.
  2. Optimization of airflow management systems by coupling optimization engine with fast indoor airflow simulation.
  3. Simultaneous optimization of airflow management and cooling system by seeking a global optimal solution via coupled simulation of both systems.

Impact

At a target level of performance (**30% saving in cooling energy**), a nationwide adoption of this tool will potentially reduce annual electricity usage by 21 billion kWh and save about $2.2 billion. The target market size is estimated to be about $593 million in 2020.

The impact can be achieved by making the tool into three independent open source modules which will then allow:

- the free use of the tool for data center designers, consultants and managers;
- the modules to be integrated into DOE's tools, such as Modelica Buildings library and Spawn-of-EnergyPlus;
- the modules to be adopted and integrated into other existing data center management software by companies and other institutions.

A solid **commercialization plan** with partners will be developed:

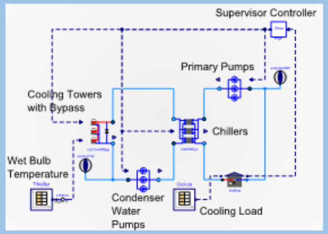
- Active engagement with various stakeholders will be performed.
- Contribution to DOE's Modelica Buildings library
- Schneider Electric, the largest data center infrastructure provider in the US, is leading the commercialization plan.

Approach: Holistic Solution with Independent Modules

Feature 1: Optimization of Cooling System Operation

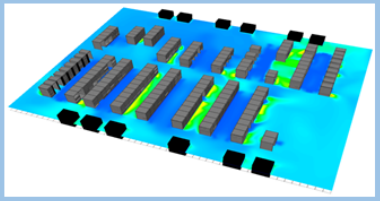
Feature 2: Optimization of Airflow Management

Module 1: Flexible Models for Cooling System



Modelica

Module 2: Self-Learning Regression Model for Airflow Management



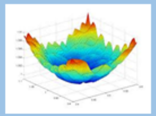
ISAT + FFD

python

python

Module 3: Optimization Engine for Cooling Optimization

GenOpt



Feature 3: Simultaneous Optimization of Airflow Management and Cooling Systems

Approach: Modelica Models for Cooling System

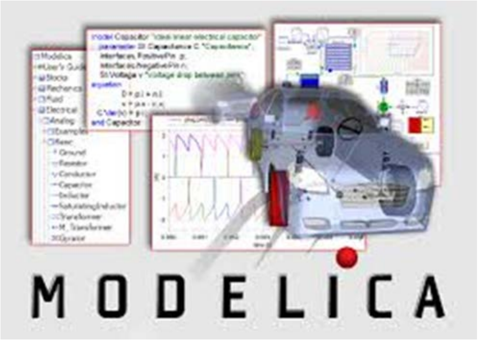
- Modelica: equation-based, object-oriented modeling language for the simulation of dynamic systems

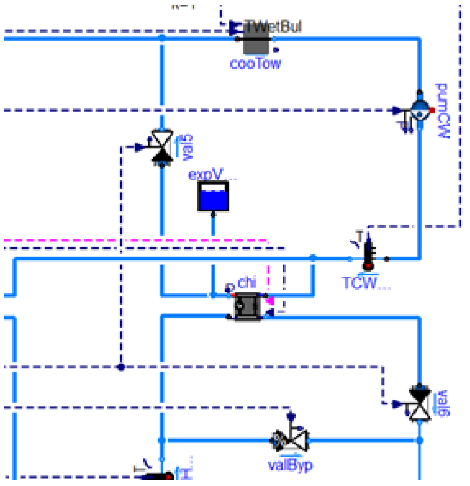
- Leverage and contribute to DOE's open source **Modelica Buildings library**[5] for building energy and control system

- Create **various component models** for data center cooling systems that allow the quick formulation of system models by dragging, dropping and connecting component models from the library.

- Provide **template system models** for reuse or adaptation to a specific data center.

- Link the Modelica models with open source GenOpt[7] optimization engine for **model-based optimization** to identify optimal control setpoints of the data center cooling system

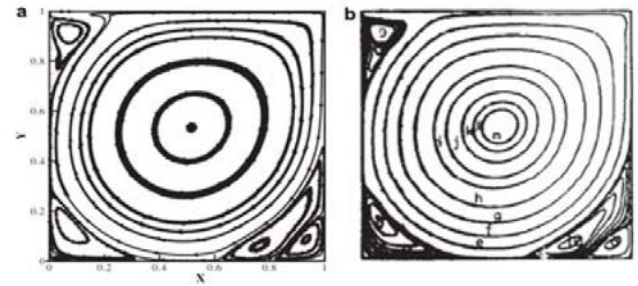




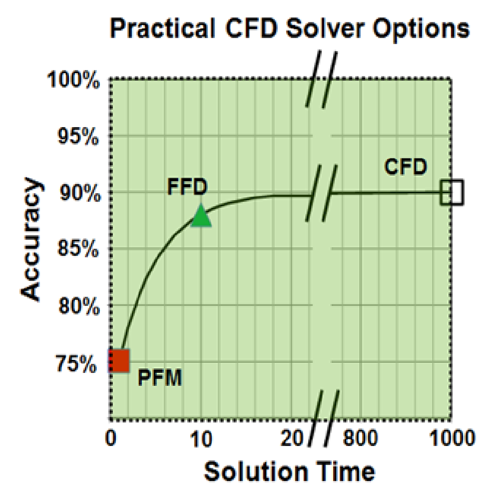
Screen shot of Modelica models

Approach: New Data Center Airflow Model

- **Fast Fluid Dynamics (FFD)** model runs 50 times faster than convectional Computational Fluid Dynamics (CFD) model with a comparable accuracy[3]
- Running FFD in parallel on **a Graphics Process Unit (GPU)** could speed up the simulation 1,200 times[21]
- **In Situ Adaptive Tabulation (ISAT):** a regression algorithm for the approximation of nonlinear relationship[4]:
  - Inputs within the region of accuracy: Linear interpolation using a data table with training data provided by nonlinear function (e.g. FFD)
  - Otherwise: call nonlinear function and grow the data table with new data from nonlinear function (**Self-learning**)
- **Coupling ISAT and FFD on GPU: a fast and self-learning model for data center airflow management**



Streamlines of a lid-driven cavity flow simulated by FFD (left) and CFD (right)[3]

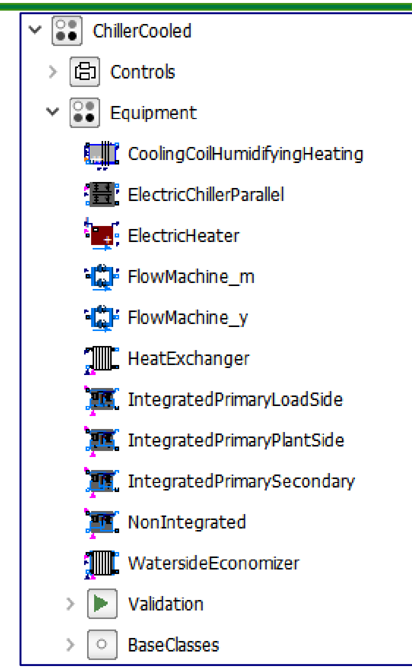


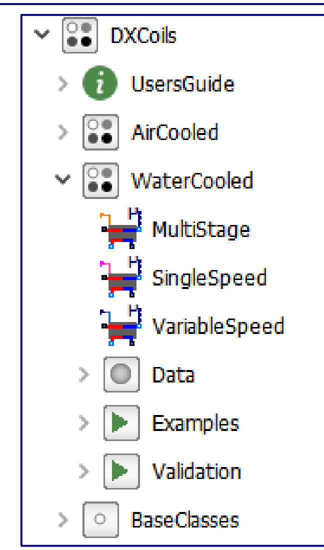
Solution time and accuracy of various data center airflow modeling methods (PFM: Potential Flow Model)[22]

Progress: New Modelica Models for Data Center

Created 81 new Modelica models in open source Modelica Buildings library (V5.0.0) which was released on 12/2017[12]. They include

- **Chilled Water System Models (58 Models):**
  - **11 Component Models**: Computer Room Air Handler, Waterside Economizers (WSEs), etc.
  - **7 Control Models**: Cooling Mode Control, Chiller Stage Control, Cooling Tower Stage Control, etc.
  - **3 System Models:** Chilled Water Systems at 3 different configurations
  - 18 **Example Models** and 19 **Base Models**
- **DX Cooled System Models (23 Models)**
  - **3 Component Models**: Single-Stage, Multiple-Stage and Variable-Speed Water Cooled Computer Room Air Conditioner (CRAC);
  - **3 Control Models**: Cooling Mode Control, Airside Economizer Control, CRAC Speed Control.
  - **1 System Model**: Variable Speed CRAC System with Airside Economizers
  - 9 **Example Models** and 7 **Base Models**

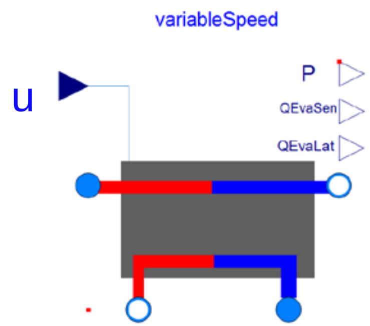




Progress: New Component Model in Modelica

All new component models for data center cooling system have (1) graphic representation as an icon; (2) diagram for implementation; (3) documentation in html embedded in the model; (4) example models for validation.

Example: Water-cooled Variable Speed Computer Room Air Conditioner (CRAC)



Icon of CRAC Model

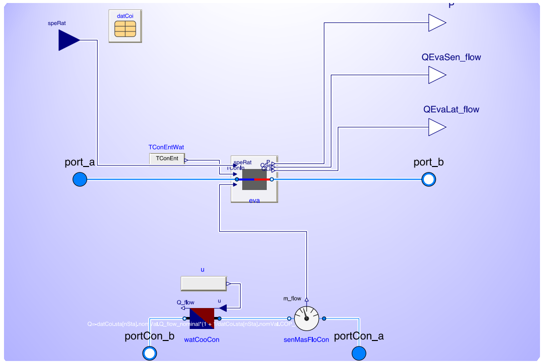


Diagram of CRAC Model

User's Guide

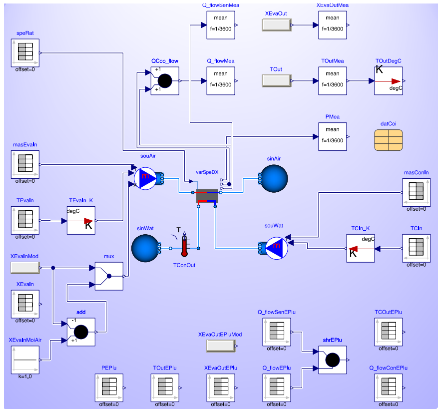
Information

This package contains models for direct evaporation cooling coils (DX coils).

The following six DX coil models are available:

DX coil condenser	DX coil model	Properties	Control signal
Air-cooled	Buildings.Fluid.HeatExchangers.DXCoils.AirCooled.MultiStage	Coil with multiple operating stages, each stage having a constant speed. Each stage has its own performance curve, which may represent the coil performance at different compressor speed, or the coil performance as it switches between cooling only, cooling with hot gas reheat, or heating only.	Integer; *0* for off, *1* for first stage, *2* for second stage, etc.
Air-cooled	Buildings.Fluid.HeatExchangers.DXCoils.AirCooled.SingleSpeed	Single stage coil with constant compressor speed	Boolean signal; `true` if coil is on.
Air-cooled	Buildings.Fluid.HeatExchangers.DXCoils.AirCooled.VariableSpeed	Coil with variable speed compressor with lower speed limit. If the control signal is below the lower limit, the coil switches off. It switches on if the control signal is above the lower limit plus a hysteresis. By default, the minimum speed ratio is `minSpeRat` and obtained from the coil data record `datCoi.minSpeRat`. The hysteresis is by default `speDeaBanRat=0.05`.	Real number; *0* for coil off, *1* for coil at full speed.
Water-cooled	Buildings.Fluid.HeatExchangers.DXCoils.WaterCooled.MultiStage	Coil with multiple operating stages, each stage having a constant speed. Each stage has its own performance curve, which may represent the coil performance at different compressor speed, or the coil performance as it switches between cooling only, cooling with hot gas reheat, or heating only.	Integer; *0* for off, *1* for first stage, *2* for second stage, etc.
Water-cooled	Buildings.Fluid.HeatExchangers.DXCoils.WaterCooled.SingleSpeed	Single stage coil with constant compressor speed	Boolean signal; `true` if coil is on.

Documentation for CRAC Model



Example for validating CRAC Model

Progress: New System Model Templates in Modelica

System Model Templates:

- provide graphic models with detailed documentation
- provide models for post-processing with visualization capacity
- allow users to build their own system models by modifying the templates

Example: Primary-only Chilled Water System with Integrated Waterside Economizer

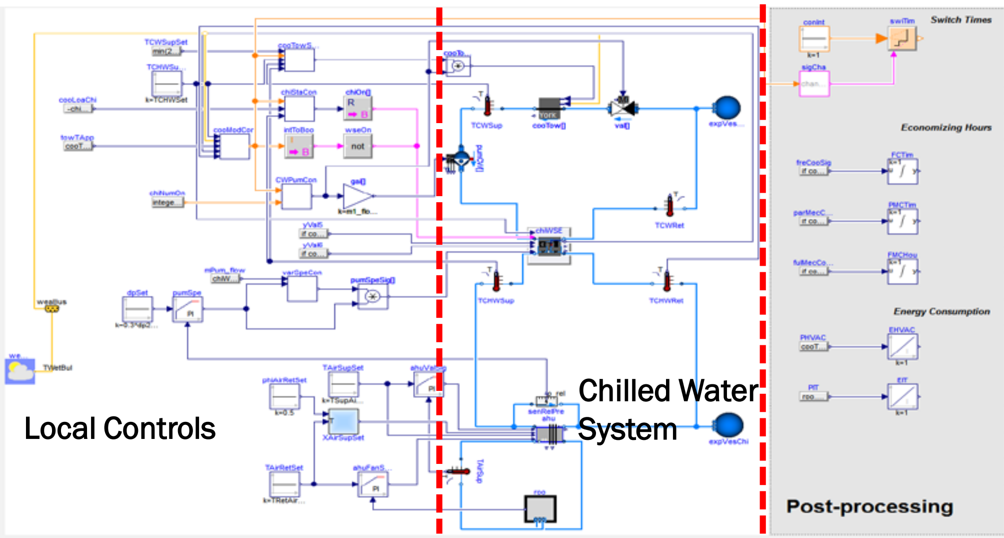
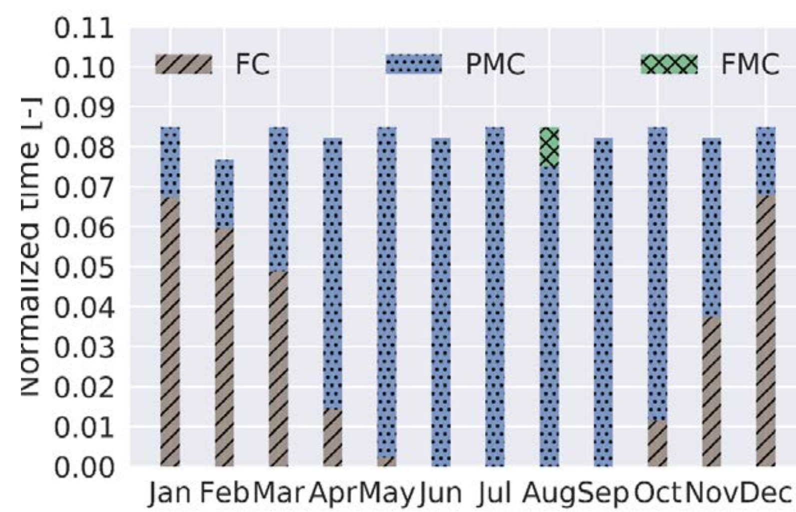


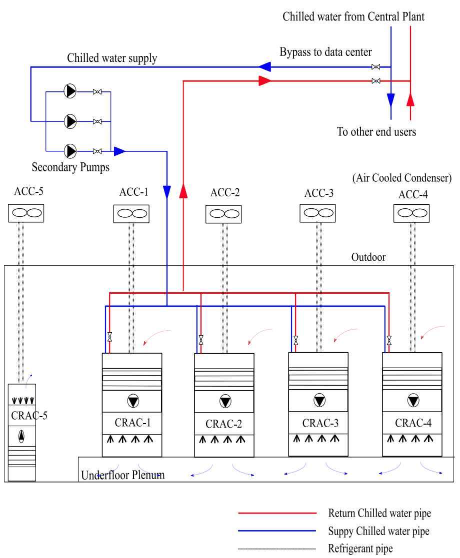
Diagram of Modelica Implementation



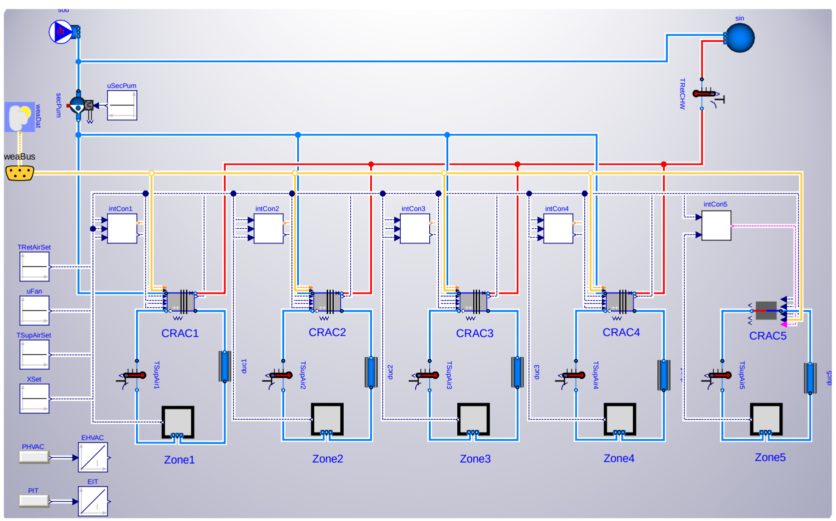
Simulated monthly normalized run time of Free Cooling (FC), Partial Mechanical Cooling (PMC), Fully Mechanical Cooling (FMC)

Progress: Demonstration at Data Center 1

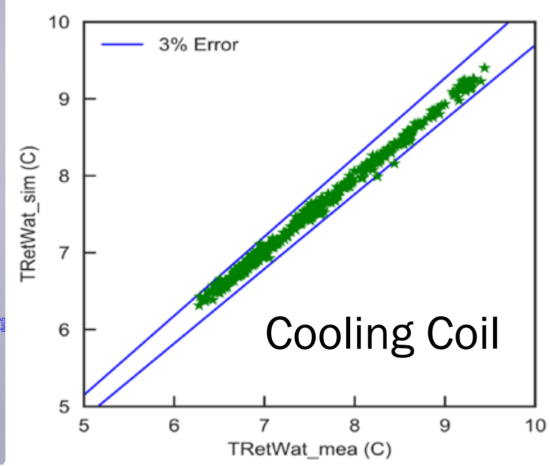
- **Location:** Florida
- **Climate Zone:** 1A – very hot and humid
- **Cooling System:** chilled water + air-cooled direct-expansion (DX) system
- **Identified energy saving measures by model-based analysis**
  - Clean cooling coil to increase the system efficiency
  - Optimize return air temperature setpoint to minimize the usage of DX system
- **Identified Potential Energy Saving: 58%**



System Schematic



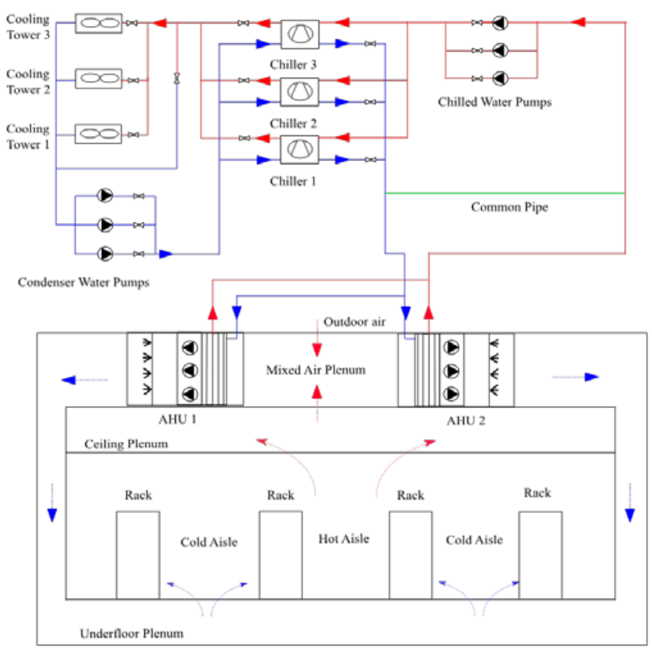
Modelica Implementation



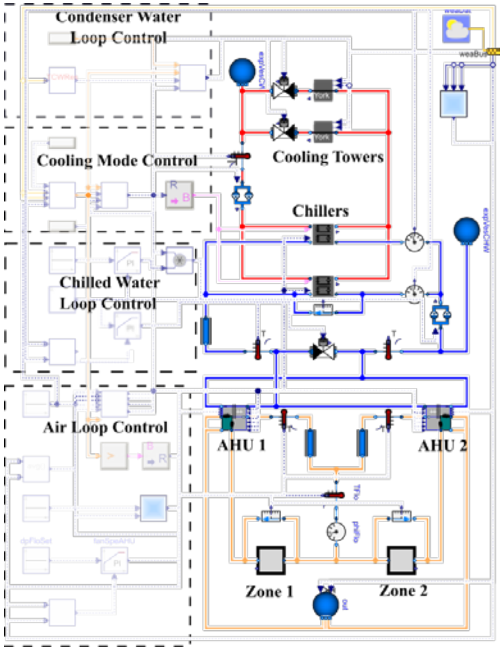
Model Validation

Progress: Demonstration at Data Center 2

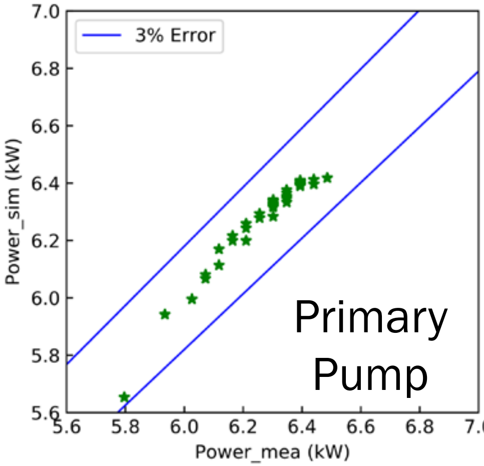
- **Location:** Massachusetts
- **Climate Zone:** 5A – cool and humid
- **Cooling System:** chilled water system + airside economizer
- **Identified energy saving measures by model-based analysis**
  - Clean cooling coil
  - Optimize cooling mode control to maximize free cooling
  - Optimize the AHU control to eliminate simultaneous heating and cooling
- **Potential Energy Saving:** 24.4%



System Schematic



Modelica Implementation



Model Validation

Stakeholder Engagement

The project is in its middle stage (Year 2 of 3-year project).

Technical Advisory Group (TAG) consisting of key stakeholders:

- Data Center Operators/Managers from universities, banks, national labs;
- Data Center Designers and Consultants;
- Experts from Federal Government and ASHRAE

TAG meetings to refine the scope of work (11/16) and review the outcome of Year 1 (03/18)

Closely working with ASHRAE data center energy calculation group (presented the project progress 3 times since 9/2016)[13-15].

TAG Institutions
Amzur Technologies
Carrier Corporation
CEC Group, LLC
JPMorgan Chase & Co.
Keystone Critical Systems & Advisors
Lawrence Berkeley National Laboratory
MITRE Corporation
Syska Hennessy Group, Inc.
University of Massachusetts Medical School
University of Miami

Engage other key stakeholders via **publications**[4, 12, 16-18], **presentations**[20], **project website** (https://www.colorado.edu/lab/sbs/doe-datacenter), and **one-to-one interactions.**

Remaining Project Work

Year 2:

- o Task 5.0: Optimization of Airflow Management System
  - Implementing and validating the ISAT-FFD models for data center airflow management
  - Demonstration at two partner data centers
- o Task 6.0: Technology-to-Market Strategy & Commercialization Plan: Phase 2

Year 3:

- o Task 7.0: Simultaneous Optimization of Data Center Cooling
  - Implementing and validating the Modelica-ISAT-FFD models for data center airflow management
  - Demonstration at two partner data centers
- o Task 8.0: Technology-to-Market Strategy & Commercialization Plan: Phase 3

Thank You

University of Colorado Boulder

Schneider Electric

Lawrence Berkeley National Laboratory

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Project Budget

Project Budget: **$522,460 (DOE), $92,168 (Cost Share)**

Variances: PI transferred from the University of Miami to the University of Colorado Boulder in 8/2017. New contract with University of Colorado Boulder is under progress. Thus, spending during the transitional period is not reflected yet.

Cost to Date:

Budget History					
9/2016– FY 2017 (past)		FY 2018 (current)		FY 2019 – 11/2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$87,141	$28,279	$250,609	$36,997	$184,710	$26,922

Progress

FY2017 focuses on implementation, demonstration and release of software feature 1
FY2018 focuses on implementation, demonstration and release of software feature 2
FY2019 focuses on implementation, demonstration and release of software feature 3

Project Schedule													
Project Start: Oct. 1, 2016		Completed Work											
Project End: Nov. 30, 2019		Active Task (in progress work)											
	◆	Milestone/Deliverable (Originally Planned)											
	◆	Milestone/Deliverable (Actual)											
	FY2017				FY2018				FY2019				
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q5 (Oct-Dec)
Past Work													
Task 1.0: Optimization of Data Center Cooling System Operation		◆		◆									
Task 2.0: Technology-to-Market Strategy & Commercialization Plan: Phase 1	◆			◆									
Task 3.0: Assessment of Airflow Management for the First Partner Data Center			◆										
Task 4.0: Release the Modelica Models and Demonstrate Software Feature 1					◆	◆							
Current/Future Work													
Task 3.5: Intellectual Property Management Plan (IPMP)						◆							
Task 5.0: Optimization of Airflow Management System						◆							
Task 6.0: Technology-to-Market Strategy & Commercialization Plan: Phase 2						◆							
Task 7.0: Simultaneous Optimization of Data Center Cooling													
Task 8.0: Technology-to-Market Strategy & Commercialization Plan: Phase 3													