

# **HVAC System Optimization with a Component Based System Model - New Version of ORNL Heat Pump Design Model**

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# Things to Do, Today



## Why I am here

- New features & interfaces of well known HPDM.
- Optimizations by use of parametric and coupling with GenOpt.

## Why listen to me

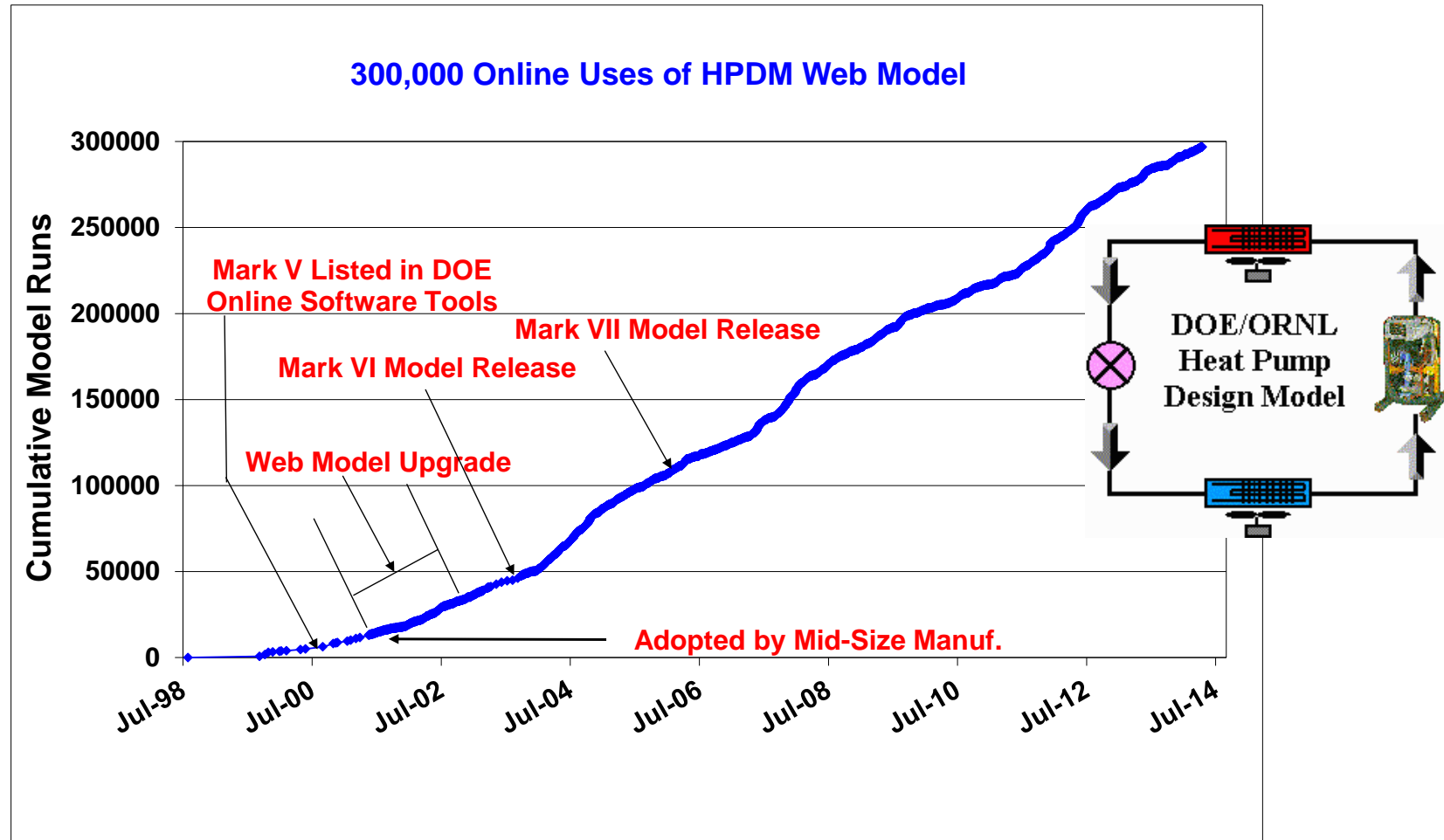
- Software is **FREE**
- Sharing best practice

## Single message to take away

*A highly capable vapor compression system modeling tool with new interfaces, advanced component models, and linkage to optimization tools, is freely available for solving heat pump design and control problems.*



# Well Regarded Web-Based HPDM



*Widely-used building equipment design software, over 30 years of development by Building Equipment Research Group, ORNL.*



# Today's Focus

## 1. HPDM New Features:

- » Extensive system configurations and flexible solving
- » Advanced heat exchanger modeling – arbitrary circuitry and 2-dimensional boundary conditions

## 2. HPDM Optimizations:

- » Flexible parametric study
- » GenOpt-coupled multiple-variable optimization

\*\* this will be a software demo, not about simulation and optimization fundamentals.

*Major release of two new interfaces: Web + Desktop (Excel Add-In)*



# Roadmap of Software Demo

Web Interface

Excel Add-In

Excel Add-In

Excel Add-In

Excel Add-In

**Quick prototype**

**Smooth connect**

**Parametrics**

**Advanced HX**

**Optimization**

1. Extensive configs
2. Component-based model
3. Graphical input and output
4. Informational wizard
5. Fast solving
6. User-controlled data source
7. P&V, flexible solving

1. Directly utilize configs from web
2. Input by component, graphically
3. Data & graphics & operation

1. Flexible inputs
2. Arbitrary data patterns
3. Built-in energy standards

1. Segment-by-segment modeling
2. Numerous HX models
3. Create arbitrary circuitries
4. Numerous tube and fin types
5. Circuitry data safe-keeping

1. 1-D search
2. 2-D contour
3. GenOpt multi-variable opt
4. Flexible inputs & solving variables
5. Flexible targets and bounds
6. Easy batch runs

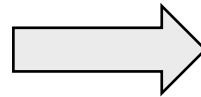
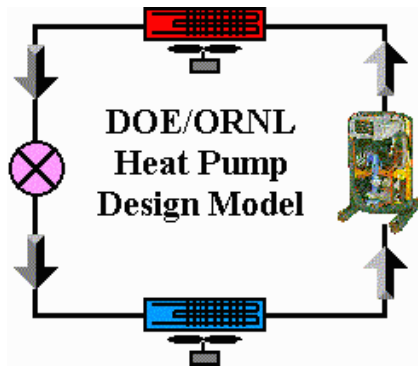
\*Demo cases will mainly use a variable-speed air conditioner and a heat pump.

***Not possible to click all the buttons today; will focus on the listed features.***



# 1.1 New Web Interface

## Previous: Single System Configuration



## DOE/ORNL Heat Pump Design Model

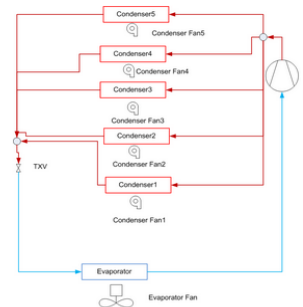
### Welcome to the new and improved HPDM on the web

The DOE/ORNL Heat Pump Design Model is a research tool for use in the steady-state design analysis of air-to-air-heat pumps and air conditioners. The WEB version has an HTML-based input interface which generates the required input text file, executes the FORTRAN application, and summarizes the results on your Web browser.

As this is a hardware-based model, the user can specify the heat exchangers and air flows and select a compressor. The flow control devices may be specified or sized by the program based on desired conditions leaving the heat exchangers. The program analyzes steady-state performance for indoor and outdoor air conditions provided by the user. An example case is provided.

The wizard will guide you through the generation of your heat-pump design model input file.

Below, you can either select an existing configuration and customize, or upload your existing configuration to begin.



## New: Extensive System Configurations

Category / Configuration	Description
▶ SC_VRF	
▶ SCWH_VRF	
▶ SH_VRF	
▶ Components	

Customize Configuration

Upload Configuration

This program was developed by the Oak Ridge National Laboratory, Building Technologies Research and Integration Center (BTRIC) under sponsorship of the Department of Energy (DOE) Program of Building Technologies.



## 1.2 New Features of Web Interface

- Extensive HVAC applications, system configurations, and numerous categories, combinations of component models.
- Hardware-based component models: edit component-by-component.
- Graphical result reporting page: contains a short list and a comprehensive list of results.
- A component model contains two kinds of inputs:
  - » P- parameters, used for model setup.
  - » V- variables, used for solving process.

Each P or V contains Name, Value, Comment, and Attribute.



## 1.2 New Features of Web Interface (contd.)

- The user controls the product data, by using download and upload buttons (web interface is only a processor).
- Flexible solving enabled by changing the variable attribute:

Required variables (values must be given):

- » **i** – input, i.e. constant in a solving process
- » **g**- guess, i.e. guess value must be provided

Optional variables (values can be empty):

- » **o**- output, i.e. only used for reporting result after each solving process; the attribute can't be changed.
- » **r** – regular, i.e. regular solving variable, the attribute can be changed to **g** or **i** with a given value.





# 1.3 Excel Add-In to Exploit All Capabilities



! Comment line to describe the system - to be inputted

A1	B	C	D	E	F	G	H
1	Comment	line to describe the system - to be inputted					
2	C	0	16	n	10001		
3	P	0	s	Map_File	0	Comp10Map.csv	
4	P	1	d	Stand_Sup	0	20	
5	V	0	i	T_Suc_Sat	0	y	50.5
6	V	1	g	T_Dis_Sat	0	y	115
11	V	6	i	Power_Ad	0	y	1
12	V	7	i	Mr_Adj	0	y	1
13	V	8	i	Heat_Gain	0	y	0.9
17	V	12	g	Superheat	0	y	20
18	V	13	g	RPM	0	y	1500
20	C	1	53	n	10001		
21	P	0	i	Substance	0	0	
23	V	1	i	DP	0	y	0.1
24	V	2	g	Tin	0	y	100
26	V	4	i	vol_flow_u	0	y	127140
27	V	5	i	Power	0	y	130
28	V	6	g	PIN	0	y	14.7
32	C	2	53	n	10001		
33	P	0	i	Substance	0	0	
35	V	1	i	DP	0	y	0.1
36	V	2	g	Tin	0	y	60
38	V	4	i	vol_flow_u	0	y	10620
39	V	5	i	Power	0	y	30
40	V	6	g	PIN	0	y	14.7
44	C	3	53	n	10001		
45	P	0	i	Substance	0	0	
47	V	1	i	DP	0	y	0.1
48	V	2	g	Tin	0	y	60
50	V	4	i	vol_flow_u	0	y	10620
51	V	5	i	Power	0	y	30
52	V	6	g	PIN	0	y	14.7
56	C	4	53	n	10001		
57	P	0	i	Substance	0	0	
59	V	1	i	DP	0	y	0.1
60	V	2	g	Tin	0	y	60
62	V	4	i	vol_flow_u	0	y	10620
63	V	5	i	Power	0	y	30
64	V	6	g	PIN	0	y	14.7

**Data**

**Graphics**

**Operation**

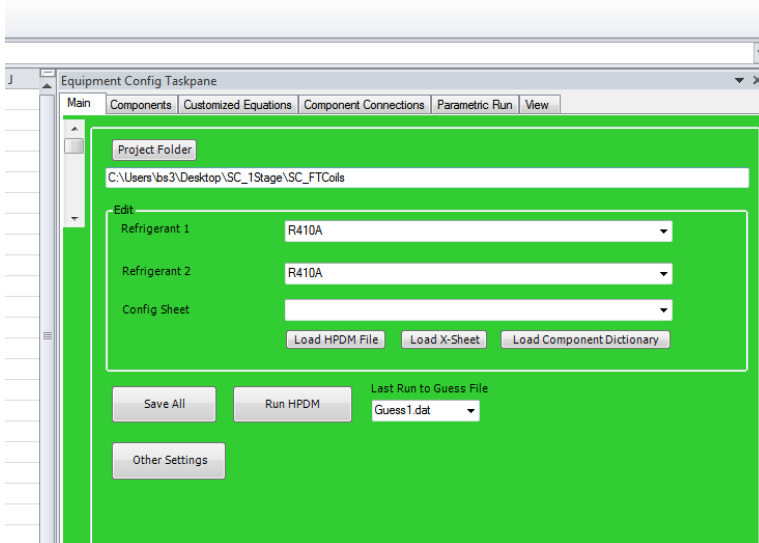
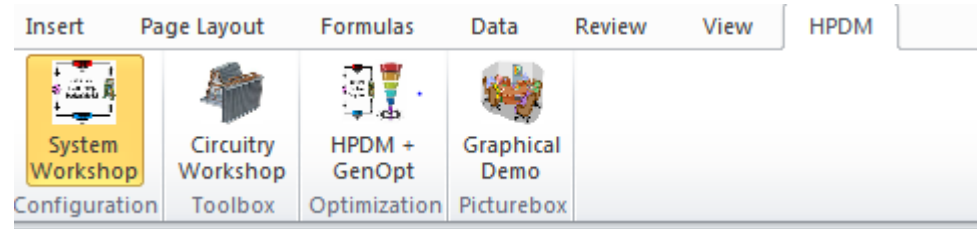
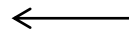
*Excel Add-in Interface enables parametric study, GenOpt optimization, SEER/HSPF calculations, constructing the system, etc.*



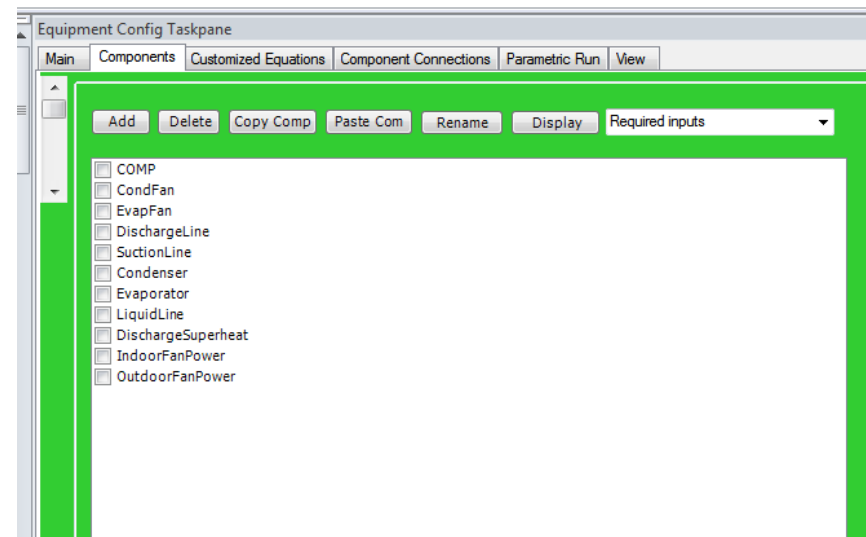
# 1.4 Excel Add-In Interface Features

- Smooth connection with Web interface – download a system configuration from web, and directly start from there.

Edit system configuration and parametric runs



System: Load-save-run



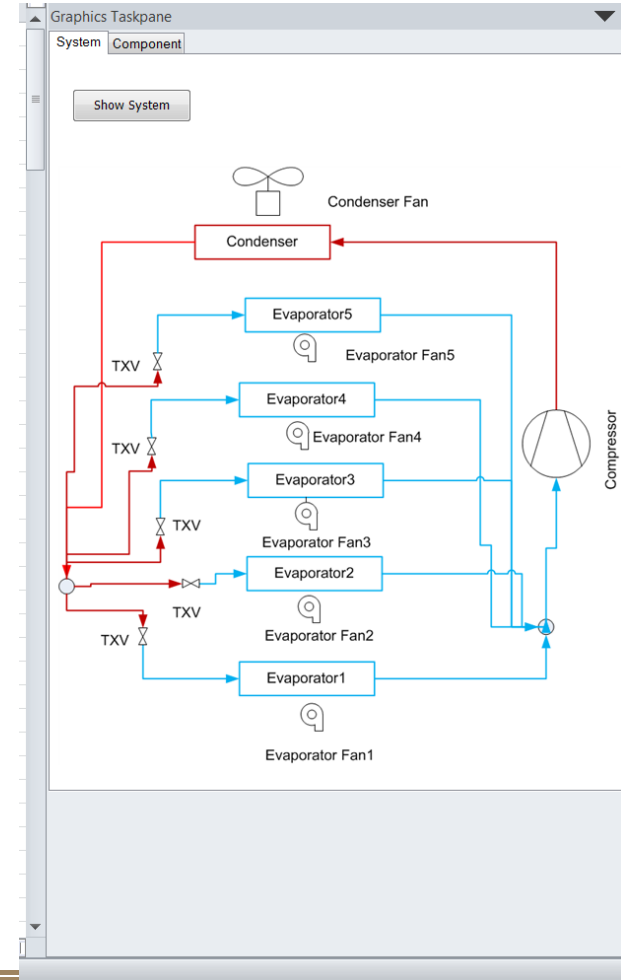
Component list: display-add-delete



# 1.4 Excel Add-In Interface Features

- Graphical demo – show data with pictures, for team discussion and demo to management.

B	C	D	E	F	G	H	I	J
6	47	n	10001					Evaporator
2	i	Evap_or_C	0		1			!
4	i	FINTYP	0		3			!
5	d	FINLEN	0		40			!
6	d	FINDEP	0		1.75			!
7	d	FINTHICK	0		0.005512			!
8	d	FINDENSI	0		160			!
9	d	FINCONDI	0		128.3			!
10	i	HOLENUM	0		80			!
11	i	TUBNUM	0		80			!
12	i	TUBTYP	0		1			!
13	d	TUBLENGT	0		30			!
14	d	CASELENG	0		30			!
15	d	TUBEID	0		0.248			!
16	d	TUBOD	0		0.276			!
17	d	TUBWTHIK	0		0.014			!
18	d	TUBCOND	0		196			!
19	d	Pt	0		1			!
20	d	Pr	0		0.875			!
21	d	RADBEND	0		0.5			!
22	i	ROWNUM	0		2			!
23	d	HTADJ_All	0		1			!
24	d	HTADJ_RE	0		1			!
25	d	DPADJ_RE	0		1.8			!
26	d	HTADJ_All	0		1			!





# 1.5 Extensive Parametric Study

	A	B	C	D	E	F	G
1	!	Comment:					
2	!	V:SysCharge:SysCharge					
3	N	500	!	number of runs for processing, and the f			
4		5	2500				
5		5.2	2500				
6		5.4	2500				
7		5.6	2500				
8		5.8	2500				
9		6	2500				
10		6.2	2500				
11		6.4	2500				
12		6.6	2500				
13		6.8	2500				

Arbitrary data pattern

Select input

List of inputs to be varied

Load Energy Standard

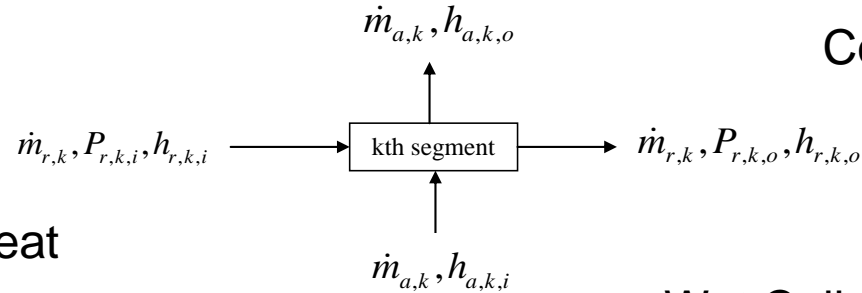
AHRI 210/240, SEER, Variable-Speed Compressor

Built-in standard test conditions for parametric run, e.g. AHRI 210/240, etc.



# 1.6 Advanced HX Modeling

## • Segment-to-segment modeling approach



Considers phase change

Dry Coil Analysis Heat Transfer

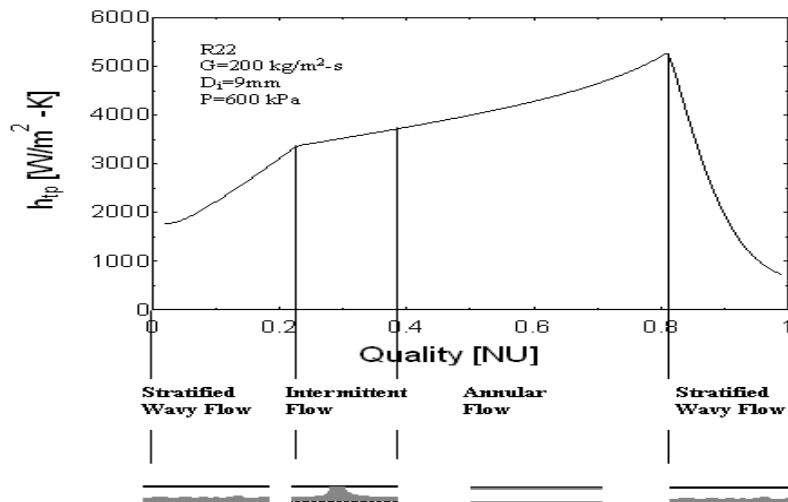
$$\dot{Q}_{\max} = C_{\min} (T_{h,i} - T_{c,i})$$

$$\varepsilon = 1 - \exp(-NTU)$$

Wet Coil Analysis Heat & Mass Transfer

$$\dot{Q}_{\max} = \dot{m}_a (h_{a,i} - h_{s, \text{evap}})$$

$$\varepsilon^* = 1 - \exp(-NTU^*)$$

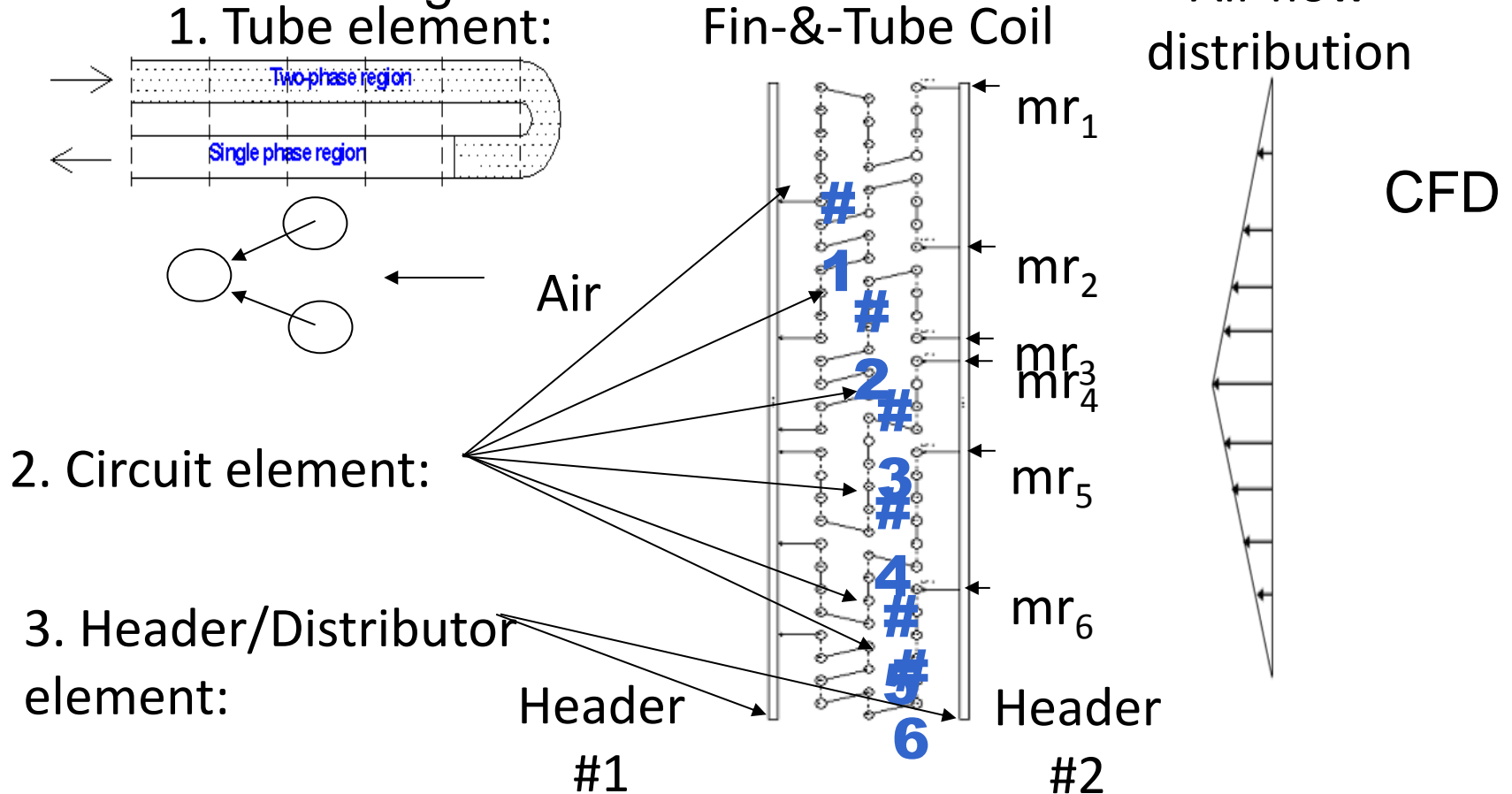


–Refrigerant side local flow-pattern-specific heat transfer calculation



# 1.6 Advanced HX Modeling

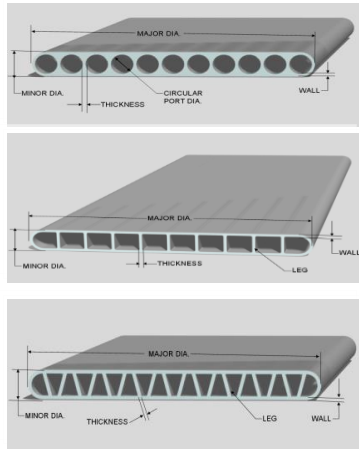
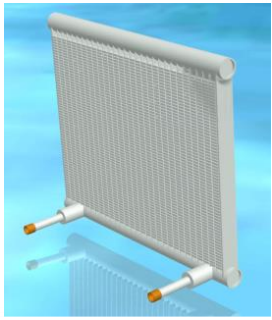
## Reality Representation: Arbitrary HX Circuitry - Segmented Fin-&-Tube Coil Modeling



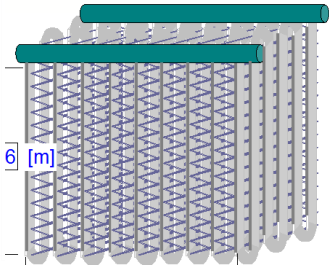
*2-D air side distribution; Independent circuit refrigerant entering conditions; Arbitrary circuitry, provides more accurate real-world heat exchanger performance predictions*



# 1.6 Other segmented HX models



**Micro-channel HX**



**Brazed Plate HX**



**Tube-in-Tube HX**



*Extensive component model library to handle majority of components used for space cooling, space heating, water heating and refrigeration.*



# 1.7 Graphical HX Circuitry Editor

SigmaPlot Graph | 
 System Workshop | 
 Circuitry Workshop | 
 HPDM + GenOpt | 
 Graphical Demo

Menu Commands | Configuration | Toolbox | Optimization | Picturebox

P18

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	
2																			
3																			
4																			
5																			
6	Air Flow	>>>>>																	
7	Air Flow	>>>>>																	
8	Air Flow	>>>>>																	
9																			
10																			
11																			
12																			
13																			
14																			
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30																			
31																			
32																			
33																			
34																			
35																			
36																			
37																			
38																			
39																			
40	Section of Boundary Condition Inputs																		
	Tube#	Seg#	Va [sfpm]	Ta [F]	RH [-]														
42	0	0	10	35	0.5														
43	0	1	10	35	0.5														
44	0	2	10	35	0.5														
45	0	3	10	35	0.5														
46	0	4	10	35	0.5														
47	0	5	10	35	0.5														

**Arbitrary tube pattern and connections**

**Facilitate tube level and segment level boundary condition inputs**

Circuitry Editor

Tube Layout | 
 Tube Connections | 
 Tube Type | 
 Fin Type

Row Number:   
 Tube Number at Front Row (include Empty Holes):   
 Segment Number per Tube:   
 Circuit Number:   
 Junction (Header/Distributor) Number:   
 Refr Flow Direction in Condenser Mode:   
 Boundary Condition Input:   
 Tube Pattern:   
 Tube Layout Sheet:





# 1.7 Graphical HX Circuitry Editor



The image displays two screenshots of the 'Circuitry Editor' software interface, showing the configuration options for heat exchanger components.

**Left Screenshot (Tube Type):**

- Tube Type: Micro-finned
- Single Phase Heat Transfer: Dittus-Boelter
- Single Phase Pressure Drop: Turbulent Flow Model
- Two Phase Evaporation Heat Transfer: Thome
- Two Phase Condensation Heat Transfer: Thome
- Two Phase Evaporation Pressure Drop: NIST-Kedzierski
- Two Phase Condensation Pressure Drop: NIST Kedzierski

**Right Screenshot (Fin Type):**

- Fin Type: Slit/Lanced
- Air Side Heat Transfer: C.C. Wang
- Air Side Pressure Drop: C. C. Wang
- Fin Geometry Inputs:
  - # of slits in an enhanced zone,  $S_n$ : 7
  - width of strip,  $S_w$ , in.: 0.0780
  - height of strip,  $S_h$ , in.: 0.0575

The right screenshot also includes diagrams illustrating fin geometries (Slit fin, one-sided and Slit fin, double-sided) and a Fin Plate View diagram showing air flow direction and fin geometry parameters.

**Numerous tube and fin types, user-selected heat transfer and pressure drop correlations.**



# 1.8 Compressor Modeling

$$Y = C_1 + C_2 T_e + C_3 T_c + C_4 T_e^2 + C_5 T_e T_c + C_6 T_c^2 + C_7 T_e^3 + C_8 T_c T_e^2 + C_9 T_e T_c^2 + C_{10} T_c^3$$

- 10-coefficient AHRI compressor map at rated inlet superheat; Y is the compressor mass flow rate or power consumption.
  - Linear interpolation between speed levels to model a variable-speed compressor.
  - Mass flow rate adjustment for actual inlet superheat levels.
- Basic efficiency compressor model: inputting compressor displacement volume, rotational speed, volumetric and isentropic efficiencies
- Other compressor models to be added as recommended.





## 2. Optimization

- Engineering optimization problems involve *at least one* objective function that is either minimized or maximized and satisfy a set of equality and inequality constraints.
  - » Maximizing energy efficiency, capacity, reliability
  - » Minimizing cost, energy consumption, materials, leaks, etc
- The result is a globally optimum design that satisfies all the problem constraint.

$$\begin{aligned} & \underset{x}{\text{minimize}} && f(x) \\ & \text{subject to:} && g_i(x) \leq 0 \quad i = 1, \dots, I \\ & && h_j(x) = 0 \quad j = 1, \dots, J \\ & && x_k^L \leq x_k \leq x_k^U \quad k = 1, \dots, d \end{aligned}$$



## 2.1 Engineering Optimization Challenges

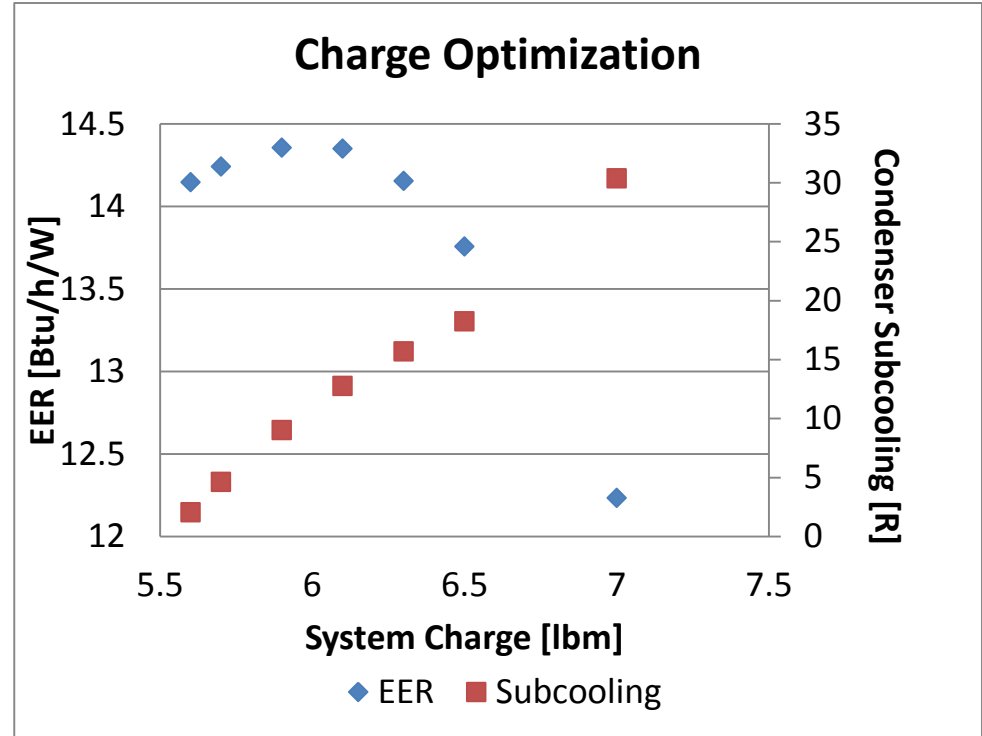


- Optimization with inaccurate models is nothing better than misleading → solution: advanced, first-principle-based models, calibrated extensively.
- We are engineers, not mathematicians → solution: user-friendly optimization interface.
- Optimization runs take long time → solution: automatic batch runs without using engineering time.



## 2.2 Parametric Analysis – 1 variable

- A local optimum can be obtained
- Good for limited range with a smooth function:  
e.g. charge optimization
  - Usually performed at the design conditions
  - Performance is plotted against charge and optimum is identified



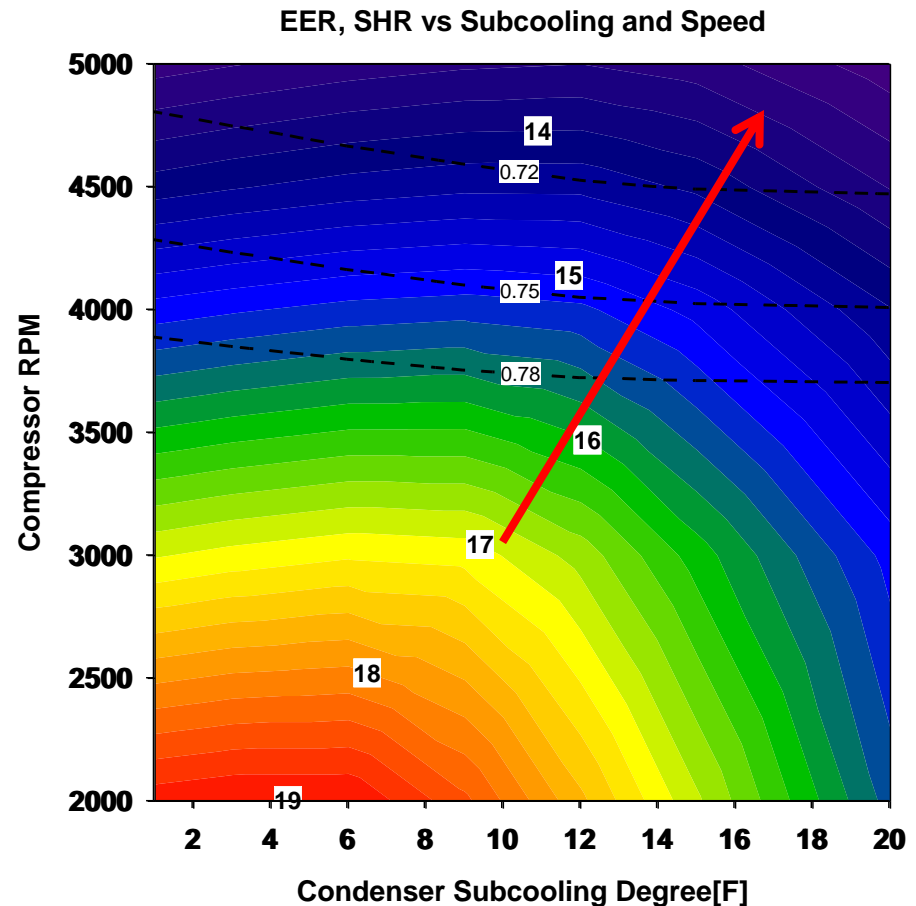
\*Vary charge to achieve optimum cooling EER in a single-stage unit.



## 2.3 Parametric Analysis – 2 Variables



- Contour plots are required to identify optimum
- Good for smooth functions only
- Constraints handling is not as easy as systematic optimization techniques
- Advantages:
  - » Simple: reasonable engineering time requirement
  - » Provides visual feedback of predicted performance trends
  - » Same results can be used for multiple optimization studies
- Limitations:
  - » Solution depend on  $\Delta X_i$
  - » Less efficient function evaluation



\*Overlay EER and SHR contours, cross-point of EER gradient line and SHR limit is the optimum

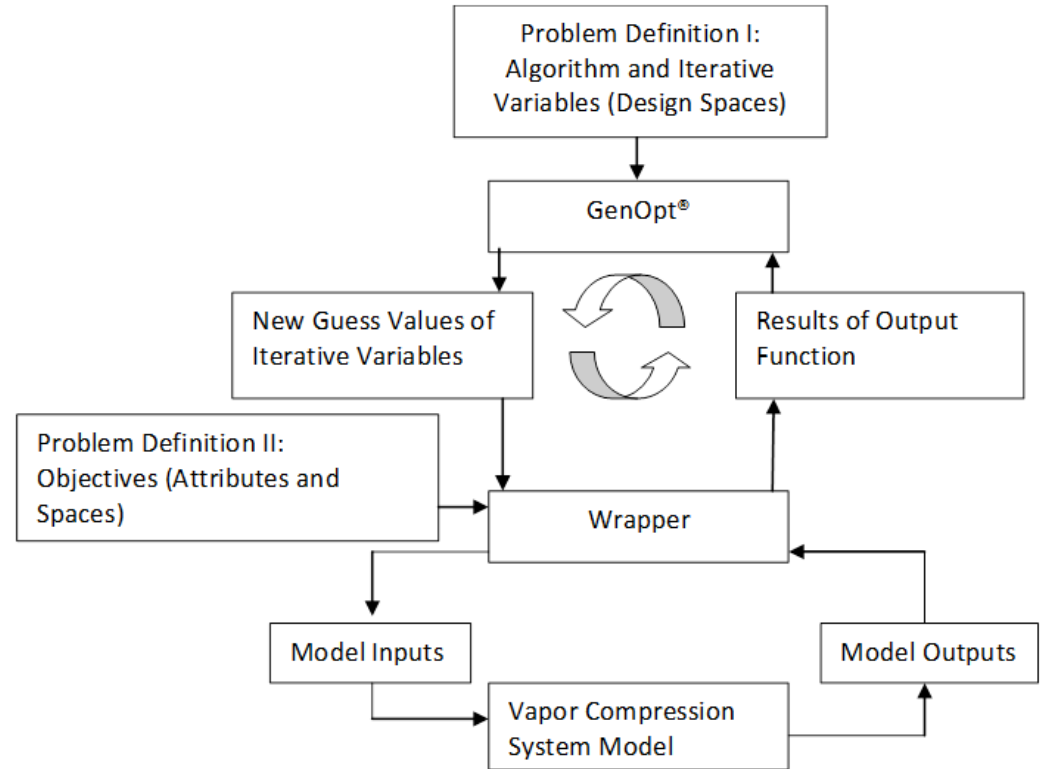


# 2.4 N Variables -- ORNL Equipment Design Optimization Tools



## ● Functionalities:

- Auto-calibration
- System optimization
- Control strategy determination



- Capable of optimizing controls in the entire operating envelope
- Using GenOpt from LBNL, open source program



## 2.5 Integrated Optimization Function



$$f(x) = \sum (W_i * OptObj_i) + \sum [T_j * (TgtObj_j - Goal_j)]^2 + \sum [P_k * (BndObj_k - Bound_k)]^2$$

- ***OptObj<sub>i</sub>*** is the value for optimization objective (*i*)
- ***W<sub>i</sub>*** is the weighting factor for optimization objective (*i*)
- ***TgtObj<sub>j</sub>*** is a value of equality constraint (*j*) and is intended to match a given target value, *Goal<sub>j</sub>* → for calibration
- ***T<sub>j</sub>*** is a weighting factor for equality constraint (*j*)
- ***BndObj<sub>k</sub>*** is a value for inequality constraint (*k*) having either upper or lower bound, *Bound<sub>k</sub>*
- ***P<sub>k</sub>*** is a penalty factor, i.e. = 0 within bounds, = infinite beyond bounds





# 2.6 HPDM + GenOpt Interface

The screenshot displays the HPDM + GenOpt interface. On the left is the 'Optimization worksheet' (Excel spreadsheet) with columns for Case No. (1-5) and rows for various components like V:Condenser:TLA, V:Condenser:HUMI, V:Evaporator:TLA, V:Evaporator:HUMI, V:SysCharge:SysCharge, V:COMP:RPM, V:CondFan:vol\_flow\_r, V:EvapFan:vol\_flow\_rs, V:EER:EER, and V:Evaporator:SHR. A green box highlights the first five rows, and an arrow points to it with the label 'Setup'. Another green box highlights the last three rows, and an arrow points to it with the label 'Batch run cases'. On the right is the 'Optimization Taskpane' with three sections: 'Input definition window' (listing components like V:Condenser:TI\_A, V:Condenser:HUMI, V:Evaporator:TLA, V:Evaporator:HUMI, V:SysCharge:SysCharge), 'Control variable window' (listing variables like V:COMP:RPM, V:CondFan:vol\_flow\_rate\_in, V:EvapFan:vol\_flow\_rate\_in with their initial, minimum, maximum, and step values), and 'Output variable window' (listing optimization goals like Optimization-->V:EER:EER W:-1 and High Bound-->V:Evaporator:SHR H:0.78).

**User friendly interface for setting up batch optimization runs.**



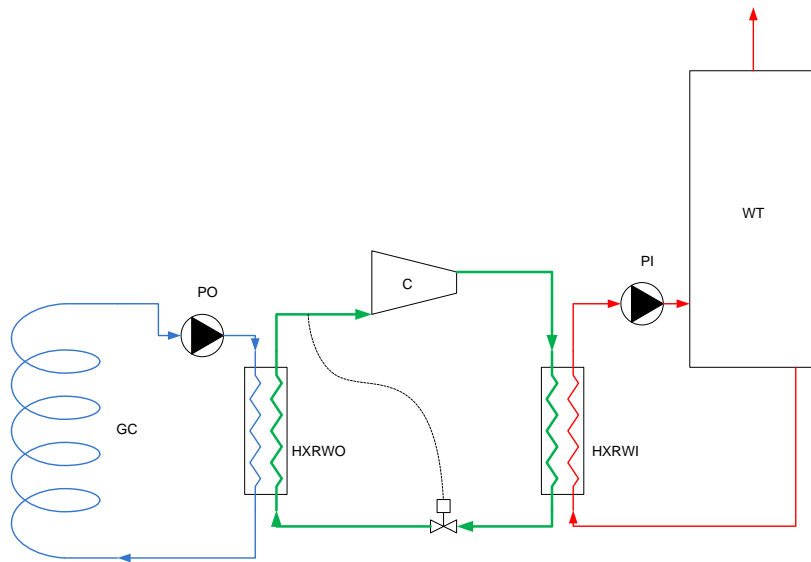
## 2.6 HPDM + GenOpt Interface

- **Inputs** – operation conditions, i.e. ambient temperatures, indoor RH, etc.
- **Control variables** – solving variables driven by GenOpt
- **Outputs:**
  - Optimization:** can be maximized (negative weight factor), or minimized (positive weight factor)
  - Target:** match a measured or required value
  - Bounds:** restrict the result within the boundaries (Low Bound, High Bound and Double Bounds)



## 2.7 A Case Study

### Variable-Speed Water Source Water Heater (2-ton)



- All variable-speed system
  - variable-speed compressor (map)
  - variable-speed water heating loop pump (curve)
  - variable-speed water source loop pump (curve)



# 2.7.1 Optimization 1: Maximize COP



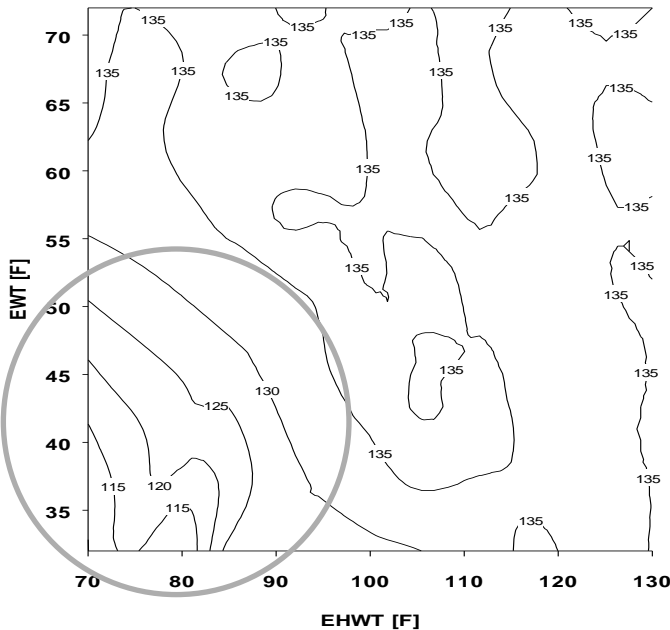
Problem Domain:

- Target water supply T @ 135°F
- Maximize WH COP
- Bounds:  $20^{\circ}\text{F} < T_{\text{sat\_suc}} < 60^{\circ}\text{F}$

3 control variables:

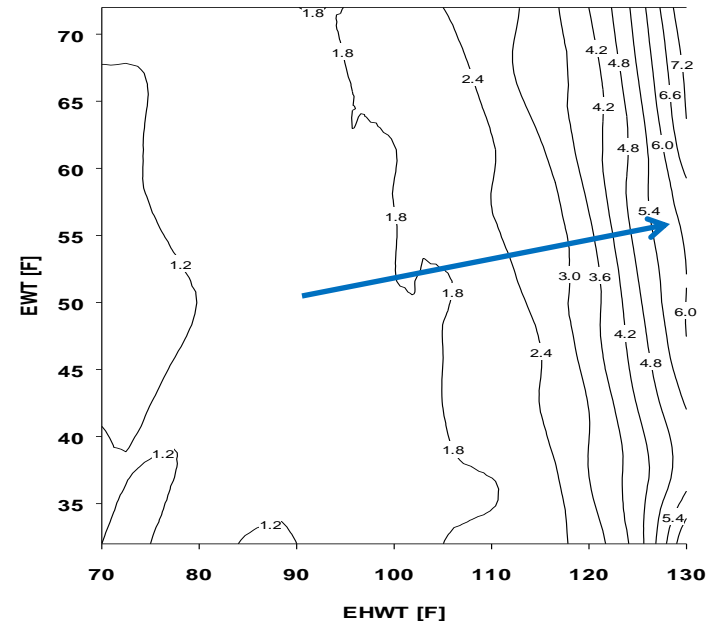
- Compressor speed (30 to 120 HZ)
- Ground pump flow (1 to 10 GPM)
- WH pump flow (1 to 10 GPM)

Water Supply Temperature [F]



At left corner,  
HPWH can't  
control  $T_{\text{supply}}$   
= 135°F @ 1.0  
GPM minimum  
WH flow rate

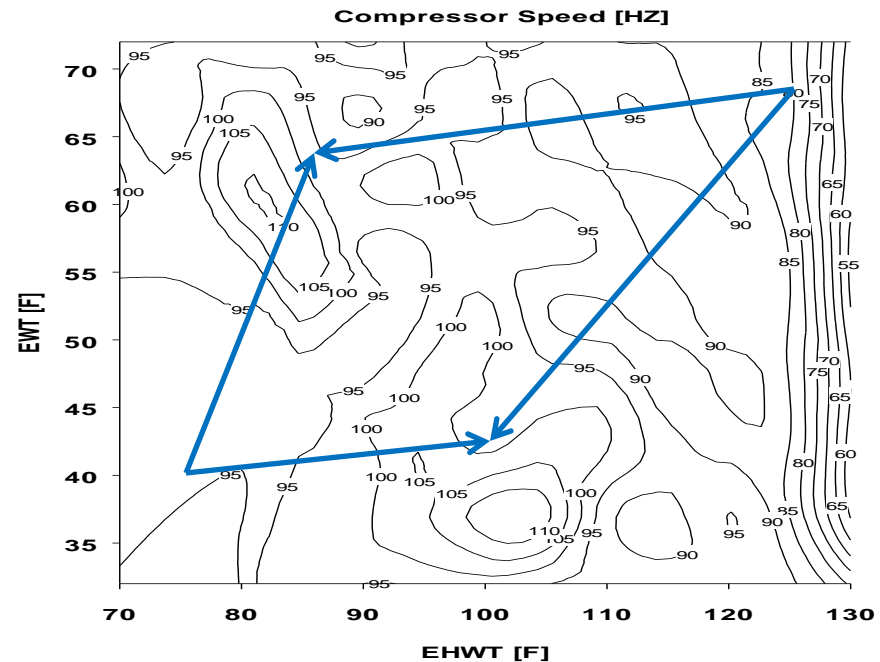
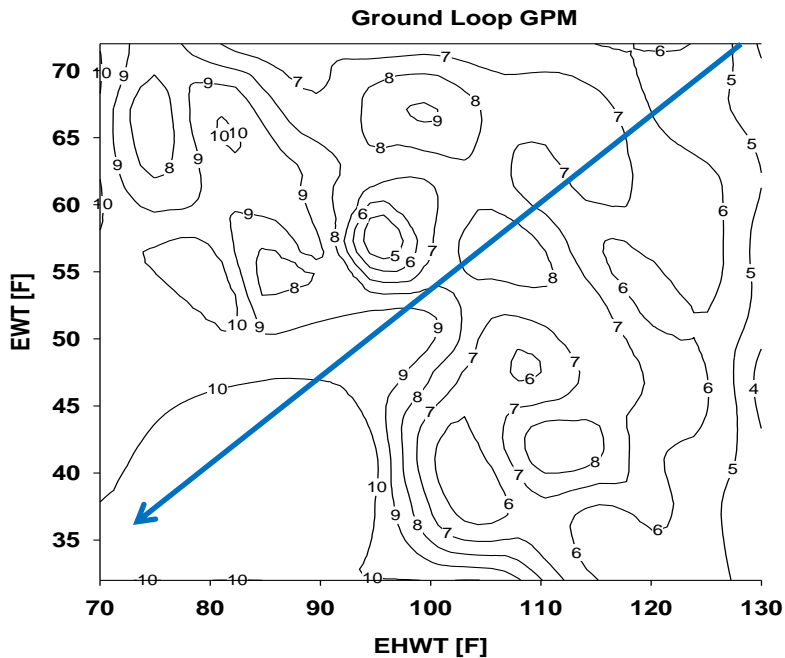
Water Heating GPM





# 2.7.1 Developing Control Functions

## Curve-Fit Adjustable Variables to Develop Control Functions



- Required ground GPM and compressor speed increase with reducing EWT and EHWT.
- Can't run max compressor speed (120 HZ) @ low EWT as this drops  $T_{sat\_suc}$  below the min 20°F constraint.

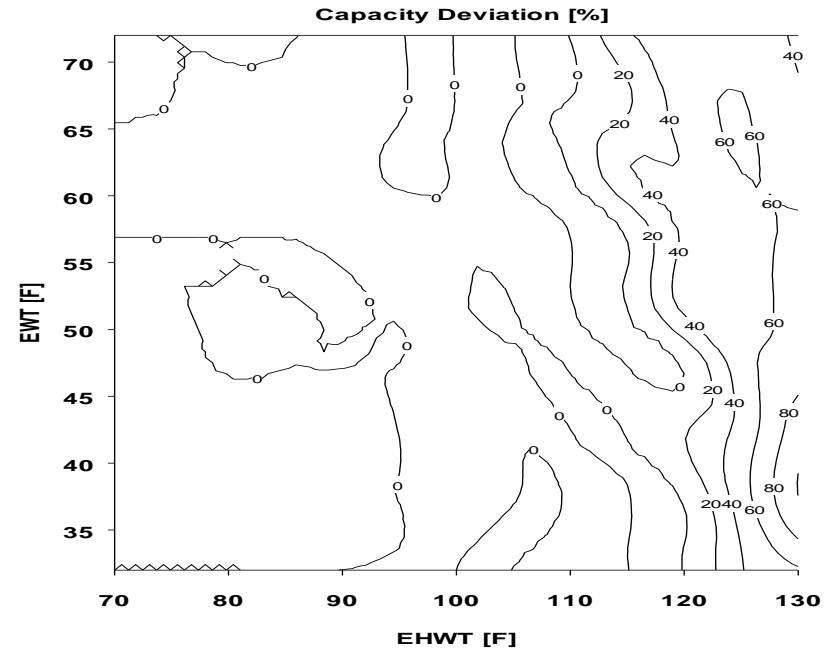
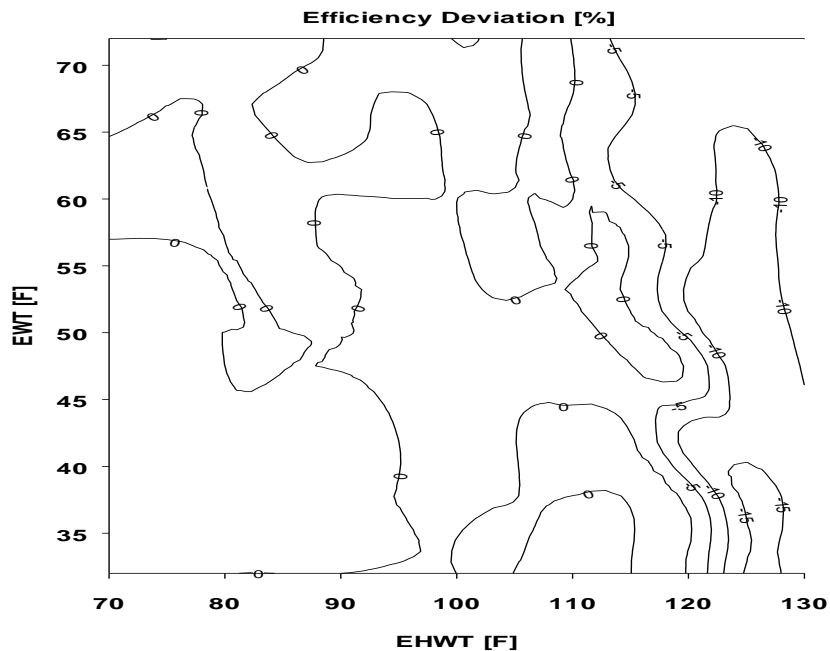


## 2.7.2 Optimization 2: Maximize COP and Capacity



### Flexibly Adding Optimization Objectives

- Maximize both WH COP and Capacity with equal normalized weights.



- Conflicting goals (equal importance).
- Increasing the capacity up to 80%,  
at the expense of reducing the efficiency by 15%.



# Summary

## New Features of Well Regarded DOE/ORNL HPDM:

- Extensive system configurations.
- Advanced component models.
- Flexible parametric study.
- GenOpt-coupled multi-variable optimization.
- Friendly user interfaces for web and desktop applications.
- ▶ FREE vapor compression system modeling tool, to support HVAC industry and research.

***Stay tuned!! The new features are going through internal testing; a trial version will be released by the end of 2014.***