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.

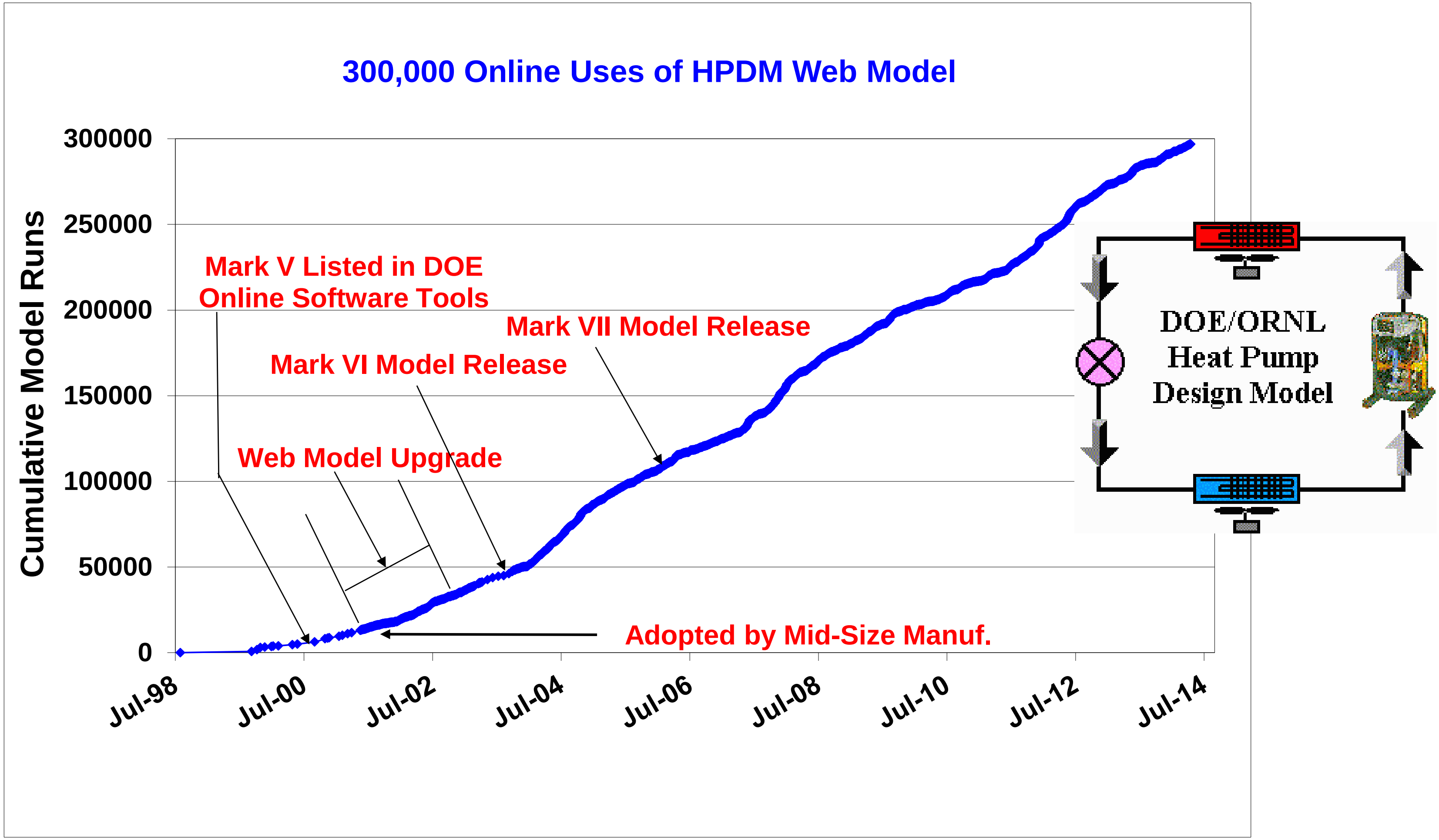
Why listen to me

- 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.

http://web.ornl.gov/~wlj/hpdm/MarkVII.shtml

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

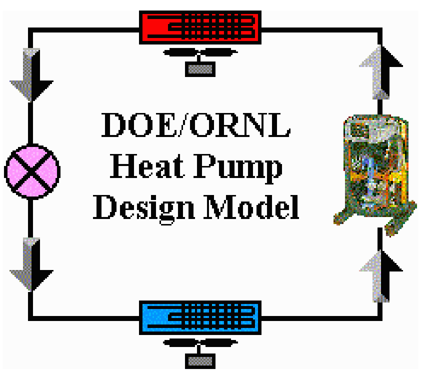
Web Interface	Excel Add-In	Excel Add-In	Excel Add-In	Excel Add-In
Quick prototype	Smooth connect	Parametrics	Advanced HX	Optimization
1. Extensive configs 2. Component-based model 3. Graphical input and output 4. Informational wizard 5. Fast solving 6. User-controlled data source 7. P&V, flexible solving	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

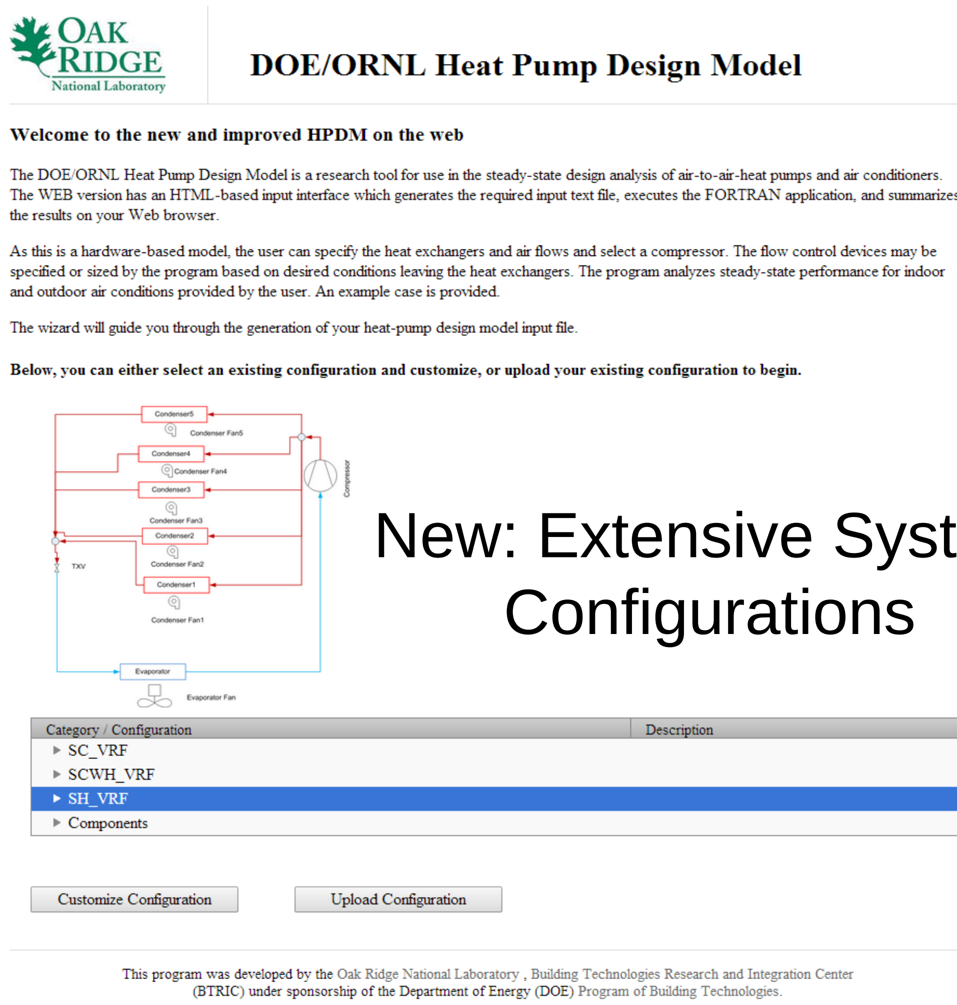
*Demo cases will mainly use a variable-speed air conditioner and a heat pump.

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

1.1 New Web Interface

Previous: Single System Configuration





New: Extensive System Configurations

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:

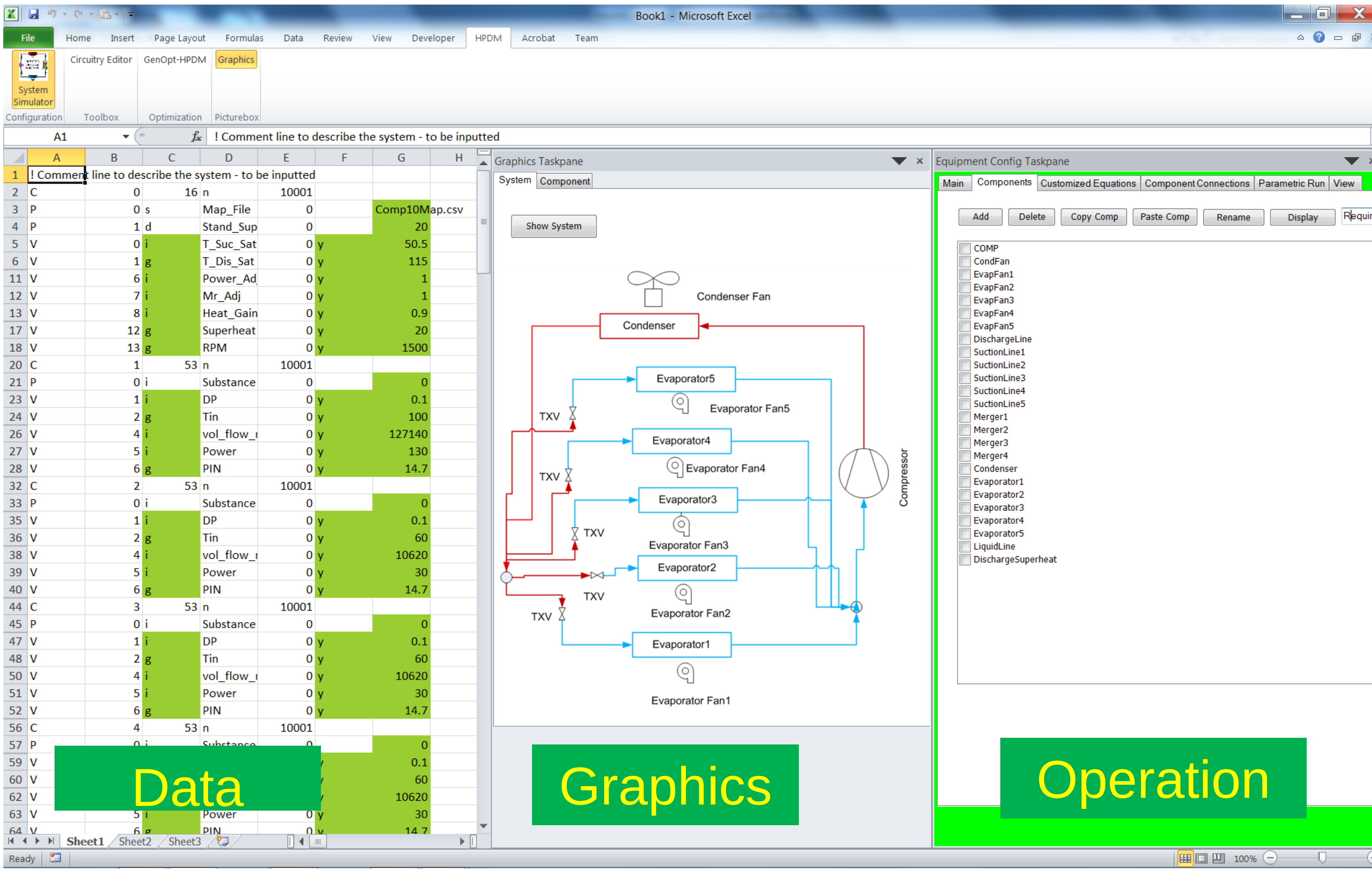
  Required variables (values must be given):

  - » **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

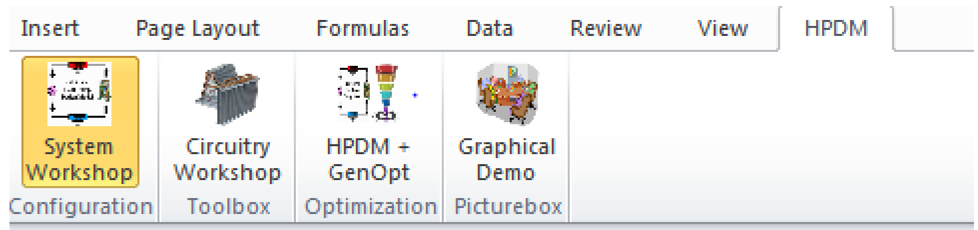


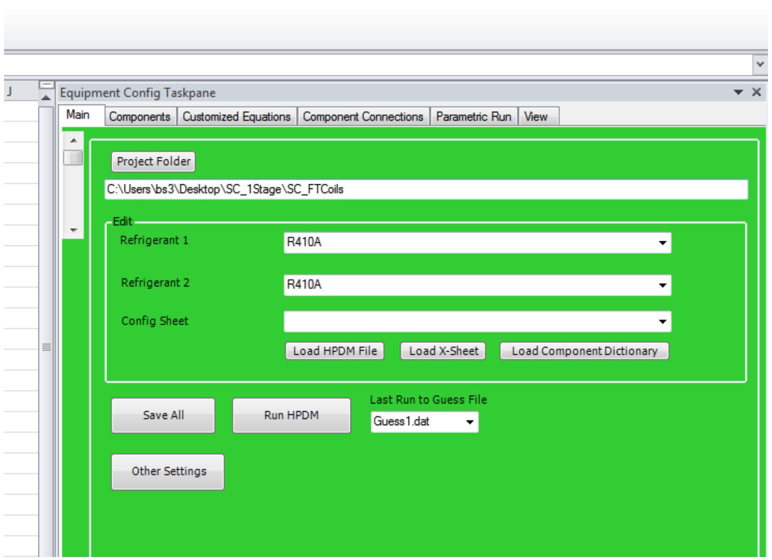
Excel Add-in Interface enables parametric study, GenOpt optimization, SEER/HSPF calculations, constructing the system, etc.

1.4 Excel Add-In Interface Features

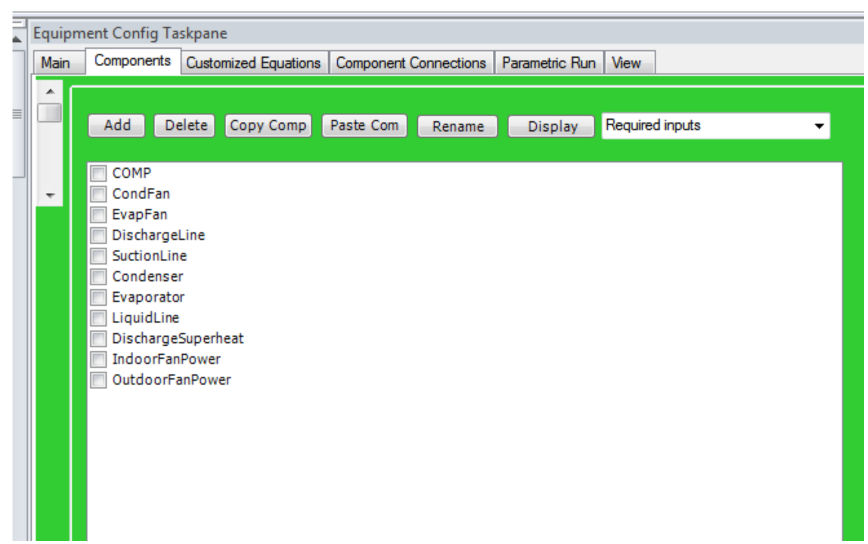
- Smooth connection with Web interface – download a system configuration from web, and directly start from there.

Edit system configuration and parametric runs ⟵





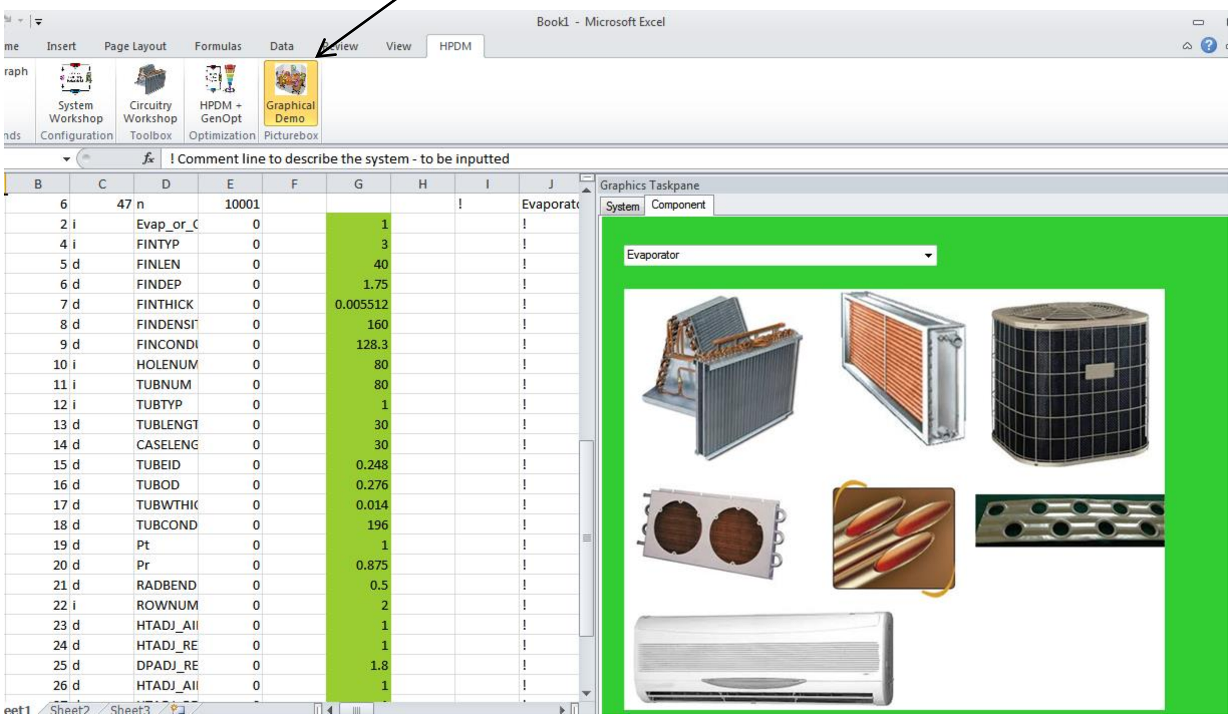
System: Load-save-run

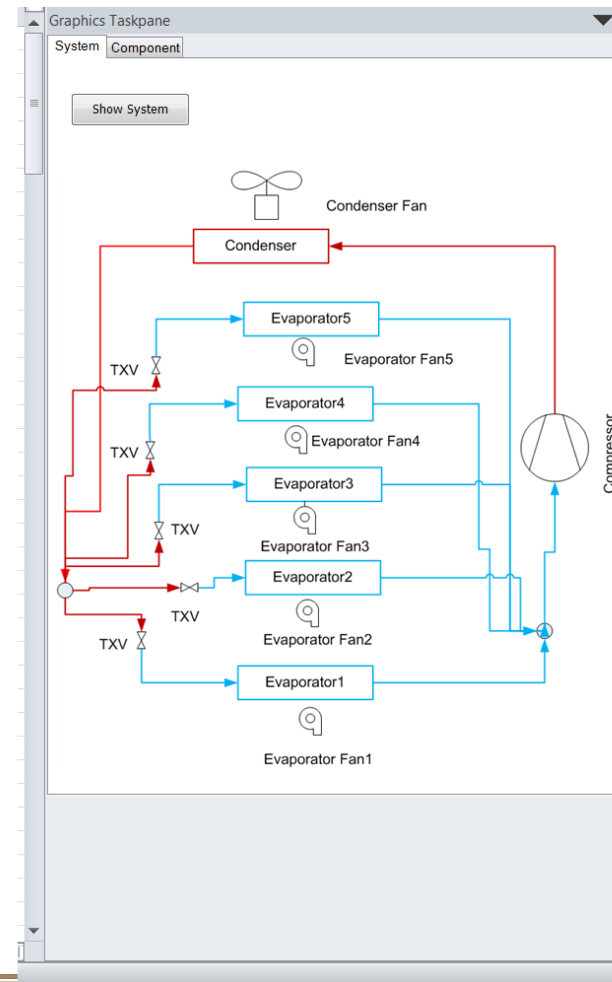


Component list: display-add-delete

1.4 Excel Add-In Interface Features

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

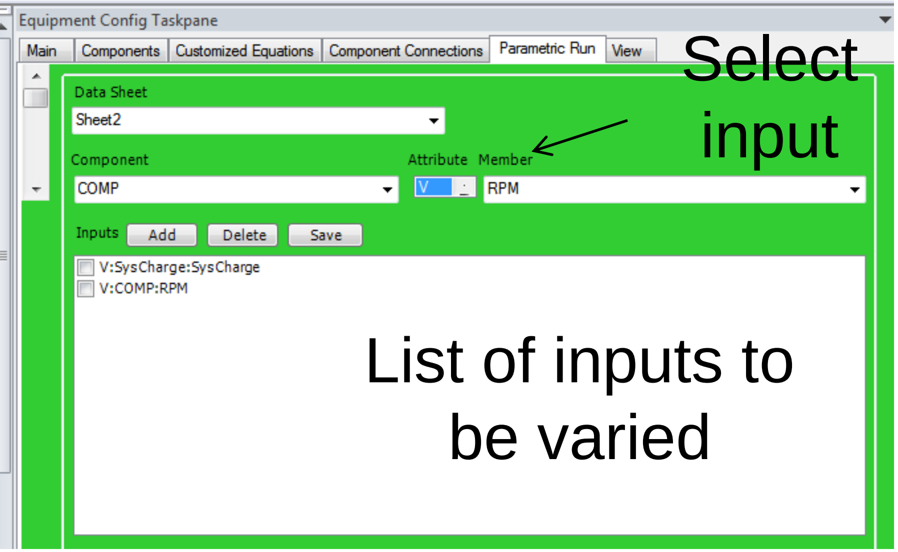




1.5 Extensive Parametric Study

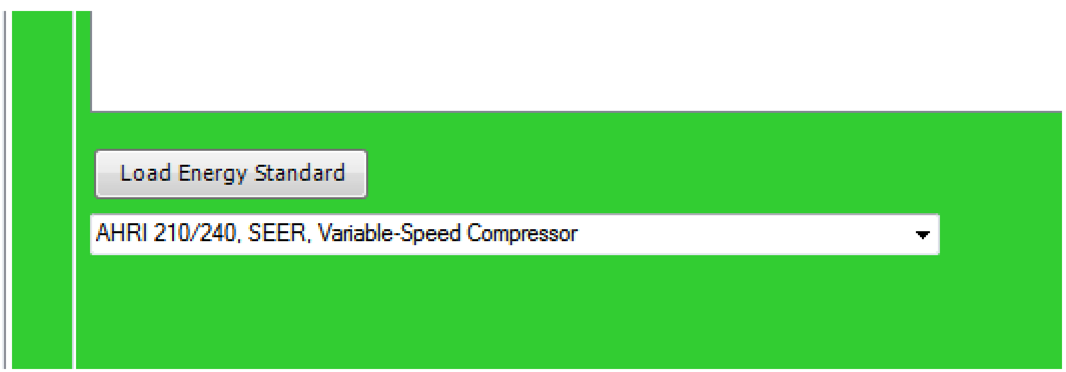
	A	B	C	D	E	F	G
1	!	Comment:					
2	! V:SysCharge:SysCharge						
3	N	500	!	number of runs for processing, and the f			
4	5	2500					
5	5.2	2500					
6	5.4	2500					
7	5.6	2500					
8	5.8	2500					
9	6	2500					
10	6.2	2500					
11	6.4	2500					
12	6.6	2500					
13	6.8	2500					

Arbitrary data pattern



Select input

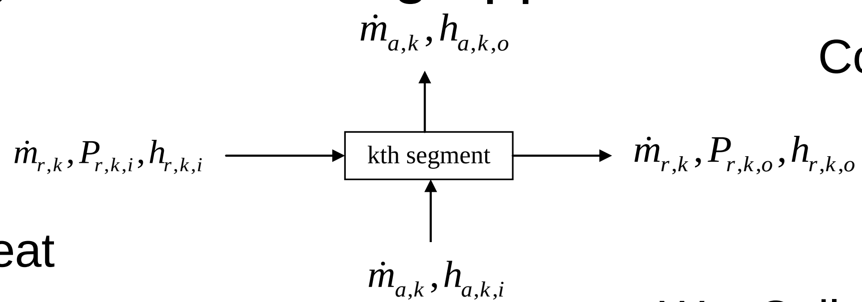
List of inputs to be varied



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

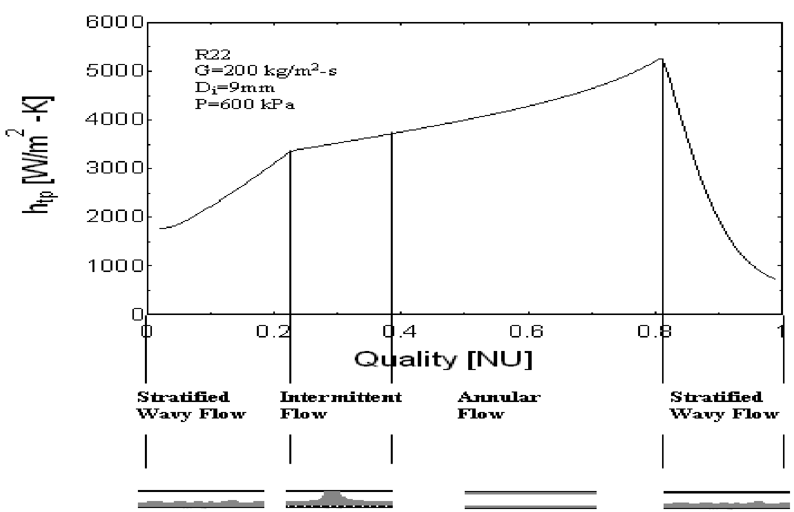
$$\dot{Q}_{\max} = C_{\min}(T_{h,i} - T_{c,i})$$

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

Wet Coil Analysis Heat & Mass Transfer

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

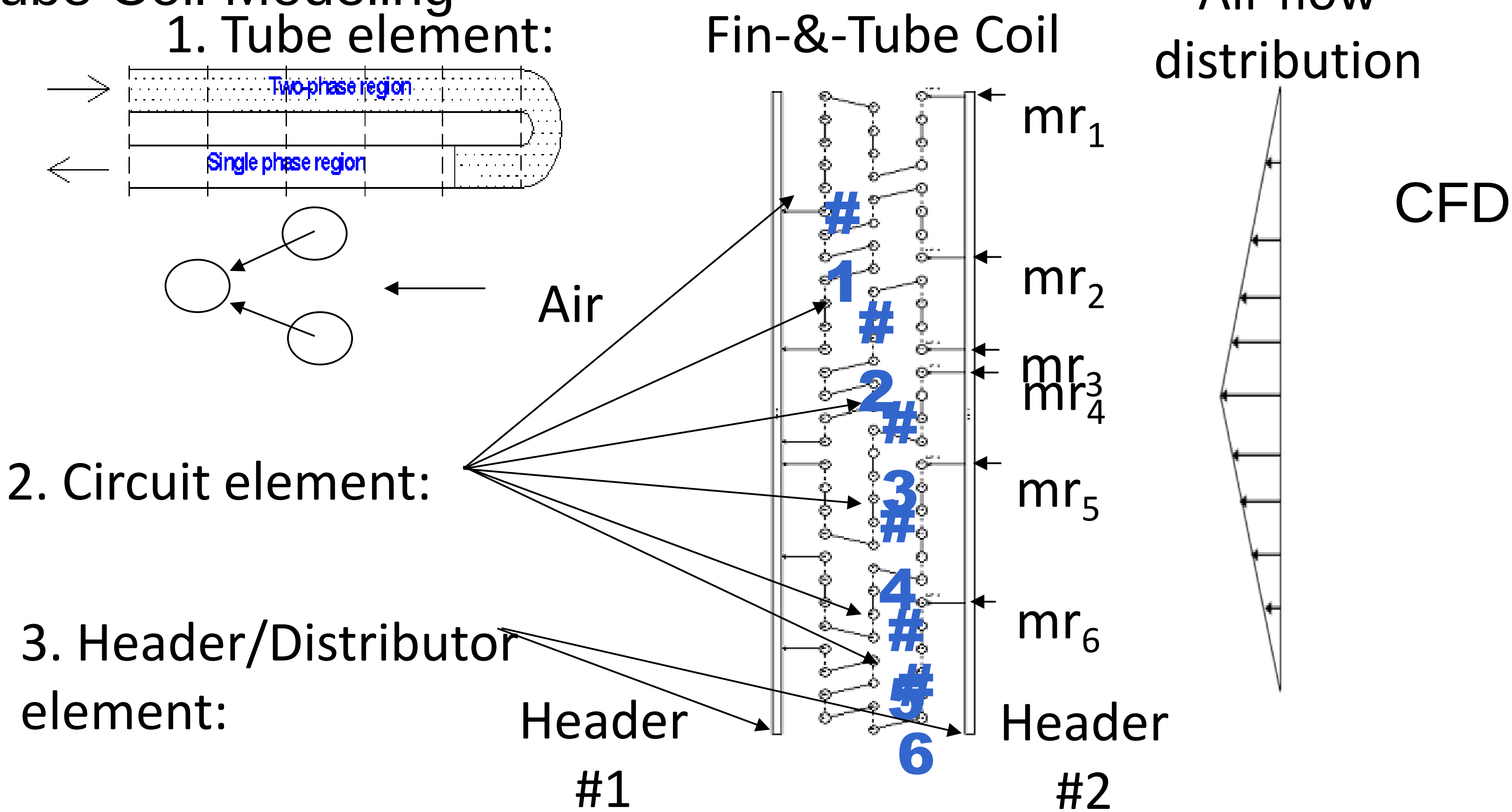
$$\varepsilon^* = 1 - \exp(-NTU^*)$$



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

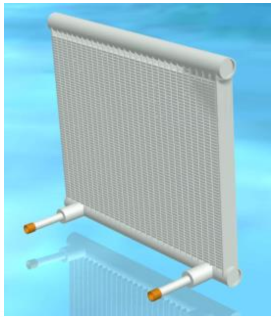
1.6 Advanced HX Modeling

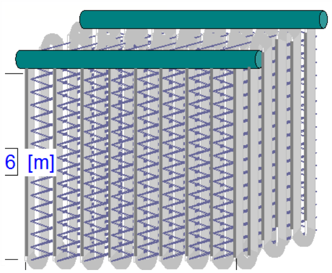
Reality Representation: Arbitrary HX Circuitry - Segmented Fin-&-Tube Coil Modeling

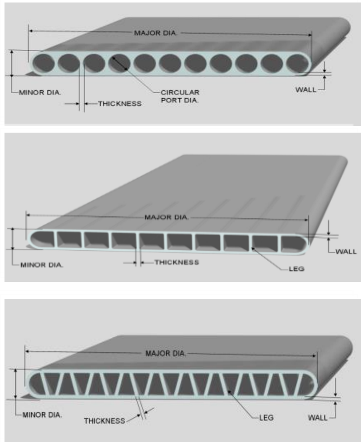


2-D air side distribution; Independent circuit refrigerant entering conditions; Arbitrary circuitry, provides more accurate real-world heat exchanger performance predictions

1.6 Other segmented HX models







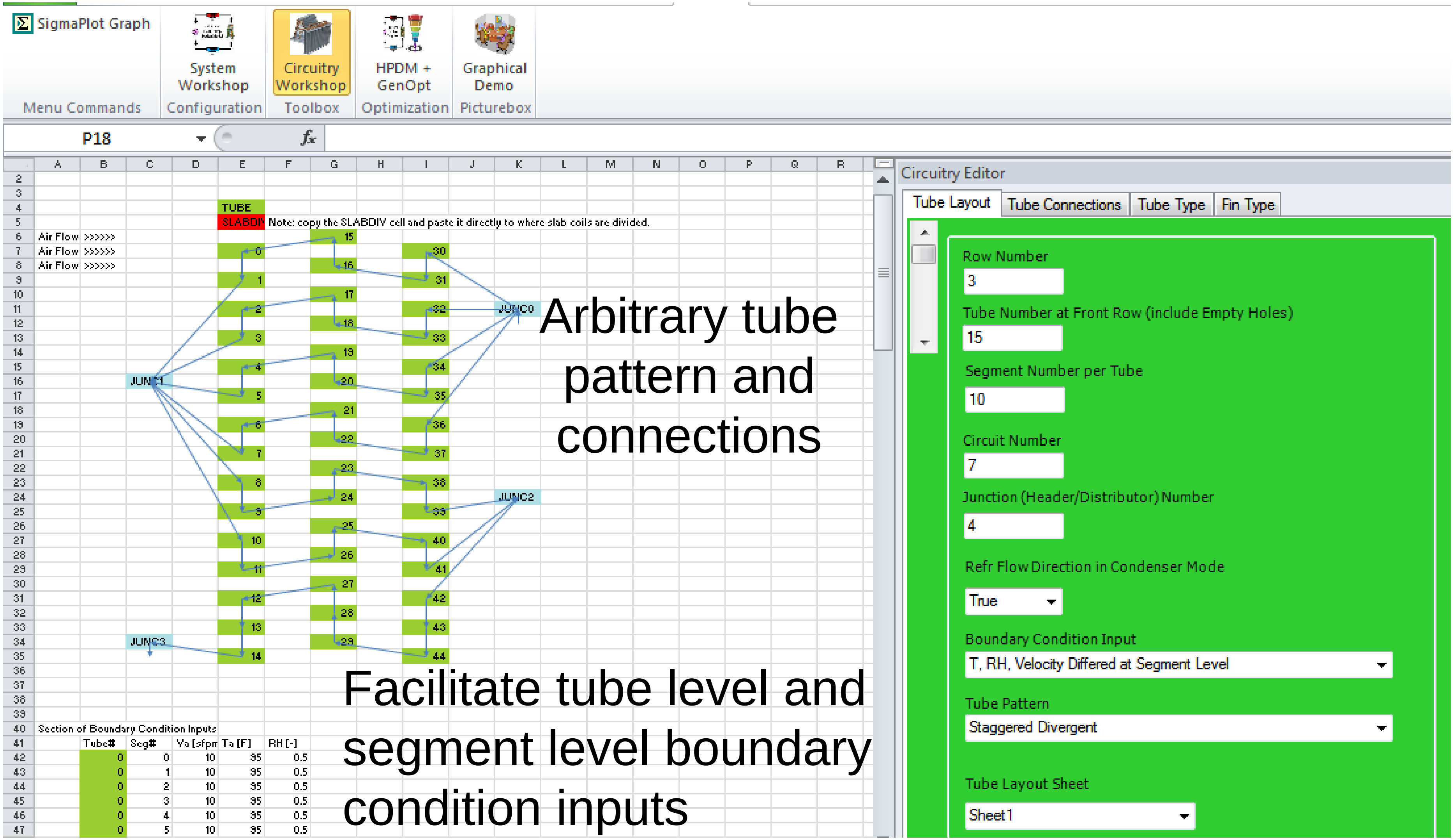
Micro-channel HX

Tube-in-Tube HX

Brazed Plate HX

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

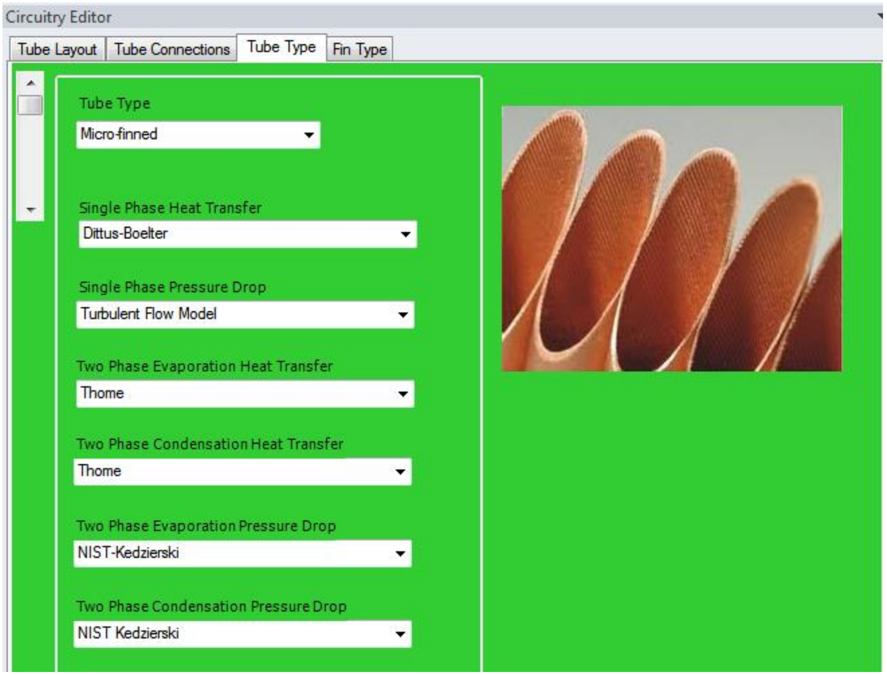
1.7 Graphical HX Circuitry Editor

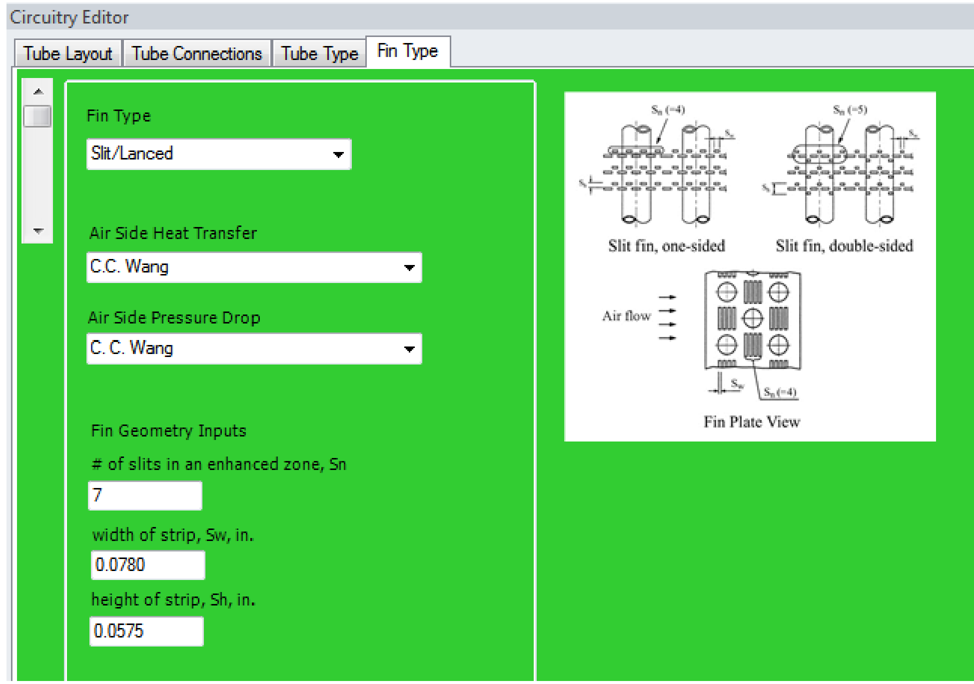


Arbitrary tube pattern and connections

Facilitate tube level and segment level boundary condition inputs

1.7 Graphical HX Circuitry Editor





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.

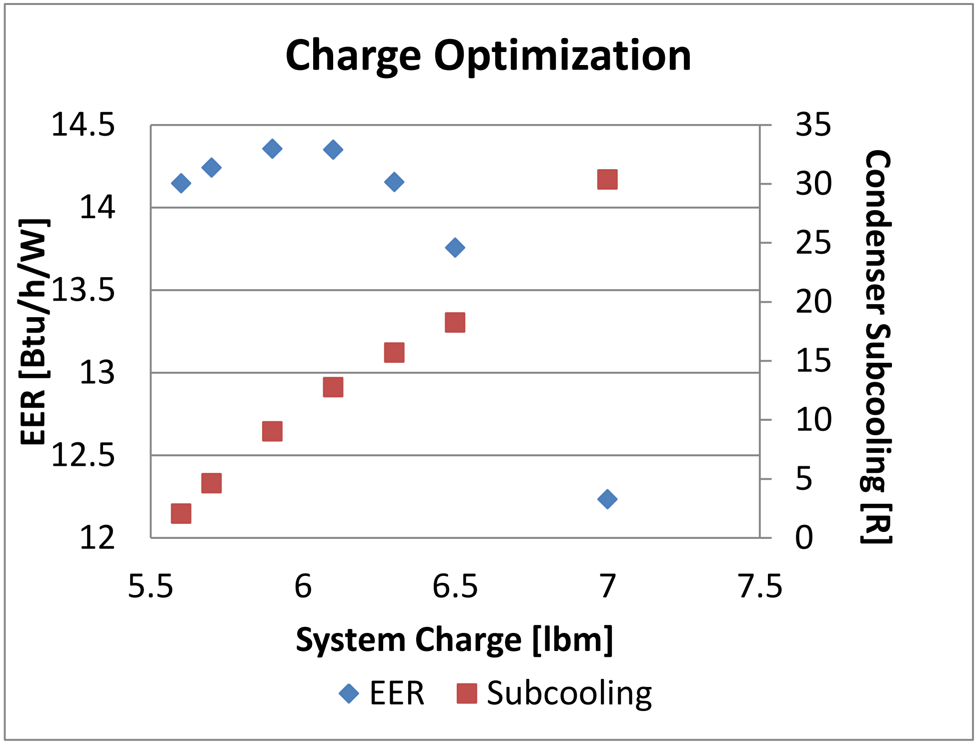
$$\begin{aligned}
&\underset{x}{\text{minimize}} \quad f(x) \\
&\text{subject to:} \; g_i(x) \le 0 \qquad i = 1,\ldots..,I \\
&\qquad h_j(x) = 0 \qquad j = 1,\ldots..,J \\
&\qquad x_k^L \le x_k \le x_k^U \quad k = 1,\ldots..,d
\end{aligned}$$

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

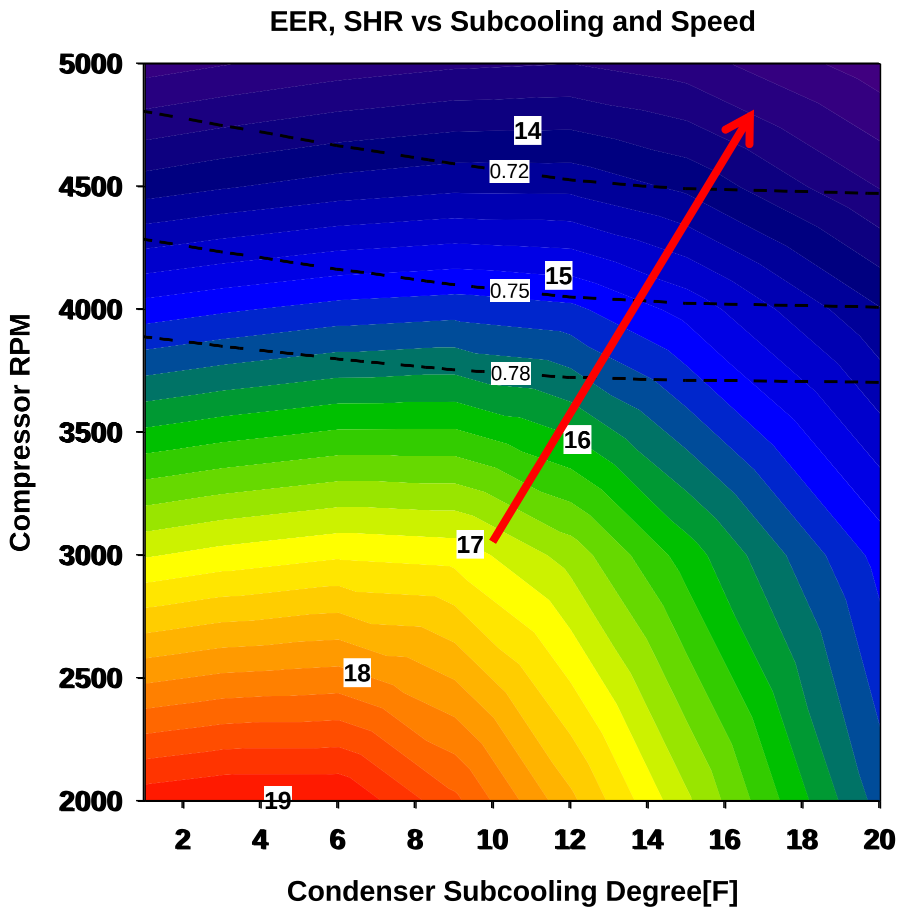
- A local optimum can be obtained
- Good for limited range with a smooth function: e.g. charge optimization
  - Usually performed at the design conditions
  - Performance is plotted against charge and optimum is identified



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

2.3 Parametric Analysis – 2 Variables

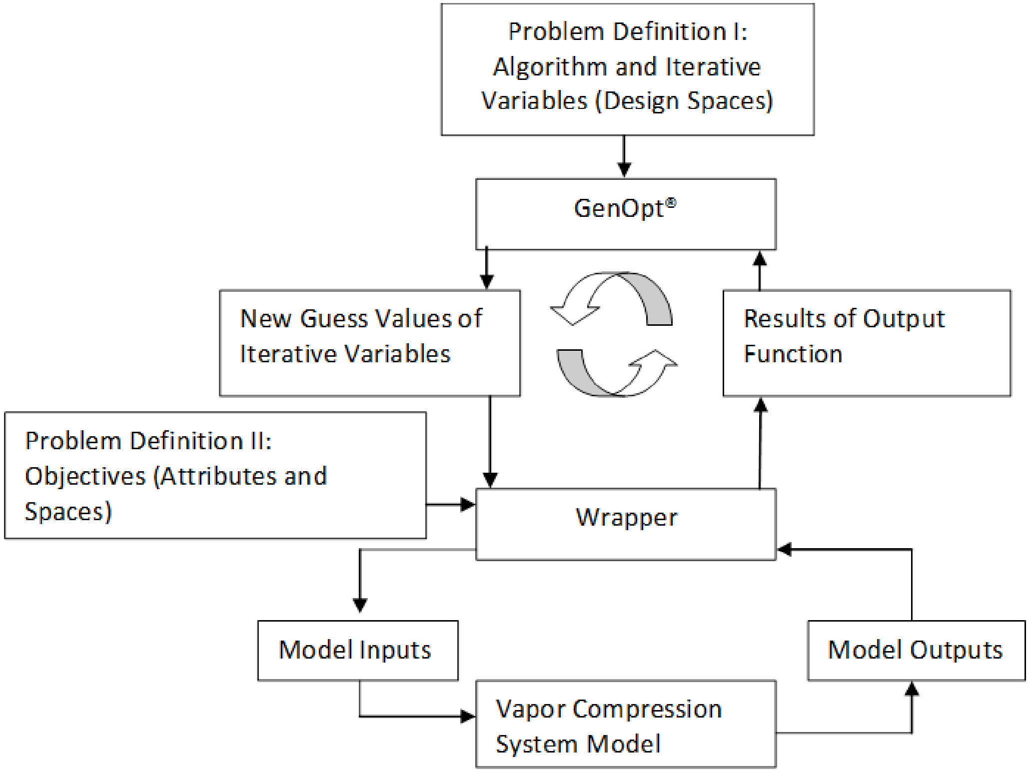
- Contour plots are required to identify optimum
- Good for smooth functions only
- Constraints handling is not as easy as systematic optimization techniques
- Advantages:
  - » Simple: reasonable engineering time requirement
  - » Provides visual feedback of predicted performance trends
  - » Same results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

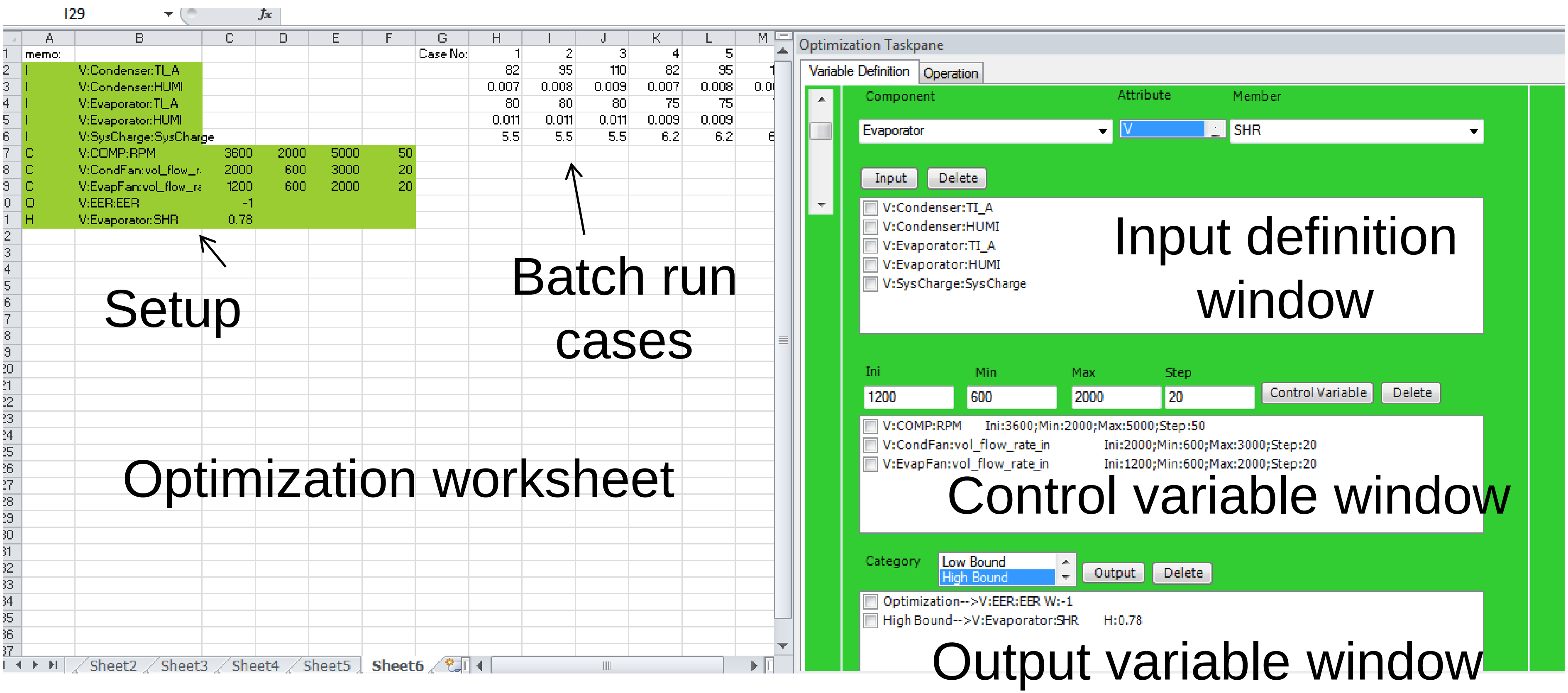
- Using GenOpt from LBNL, open source program

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

2.6 HPDM + GenOpt Interface



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:**

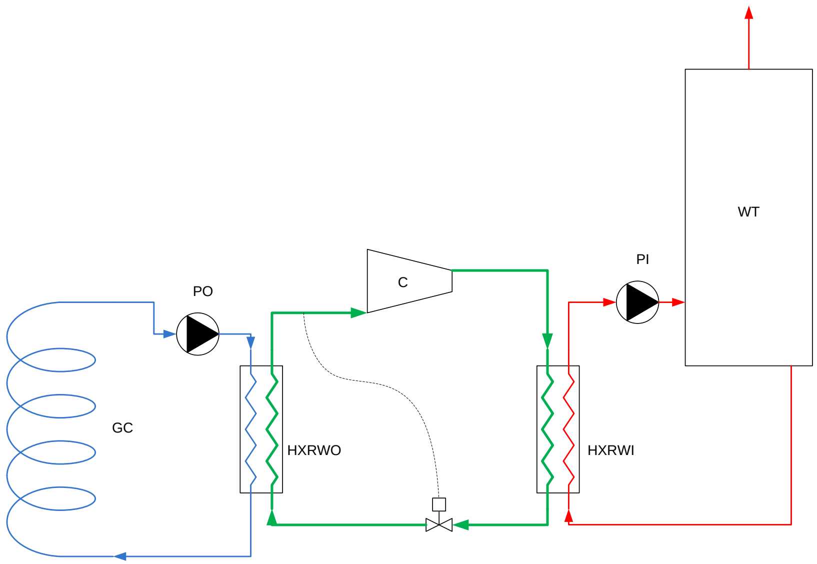
Optimization: can be maximized (negative weight factor), or minimized (positive weight factor)

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)

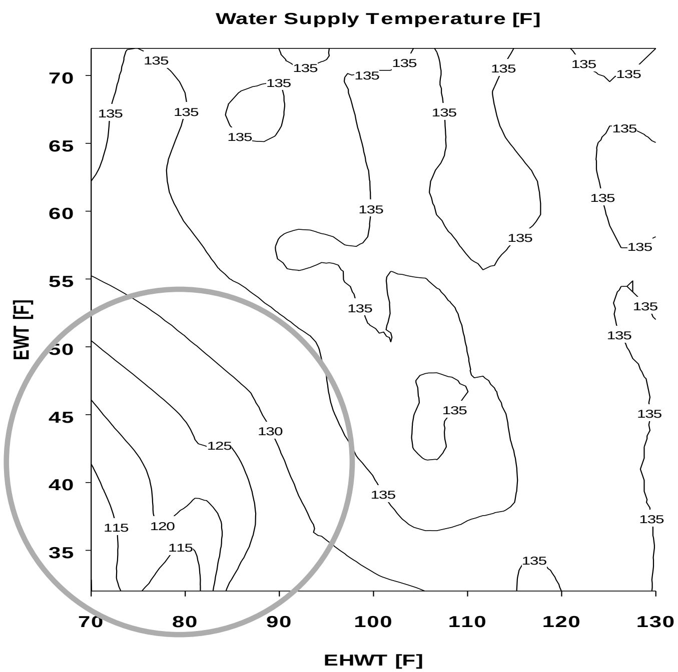
2.7.1 Optimization 1: Maximize COP

Problem Domain:

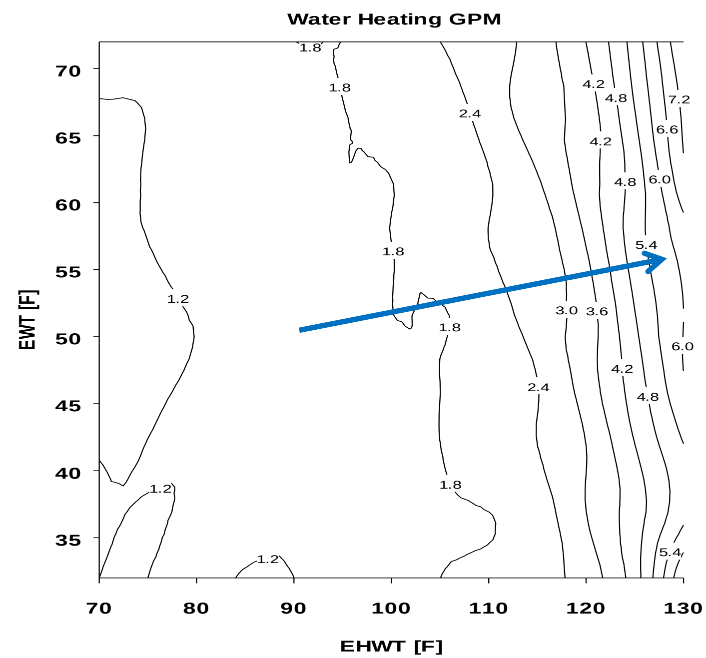
- Target water supply T @ 135°F
- Maximize WH COP
- Bounds: 20°F<T_sat_suc < 60°F

3 control variables:

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

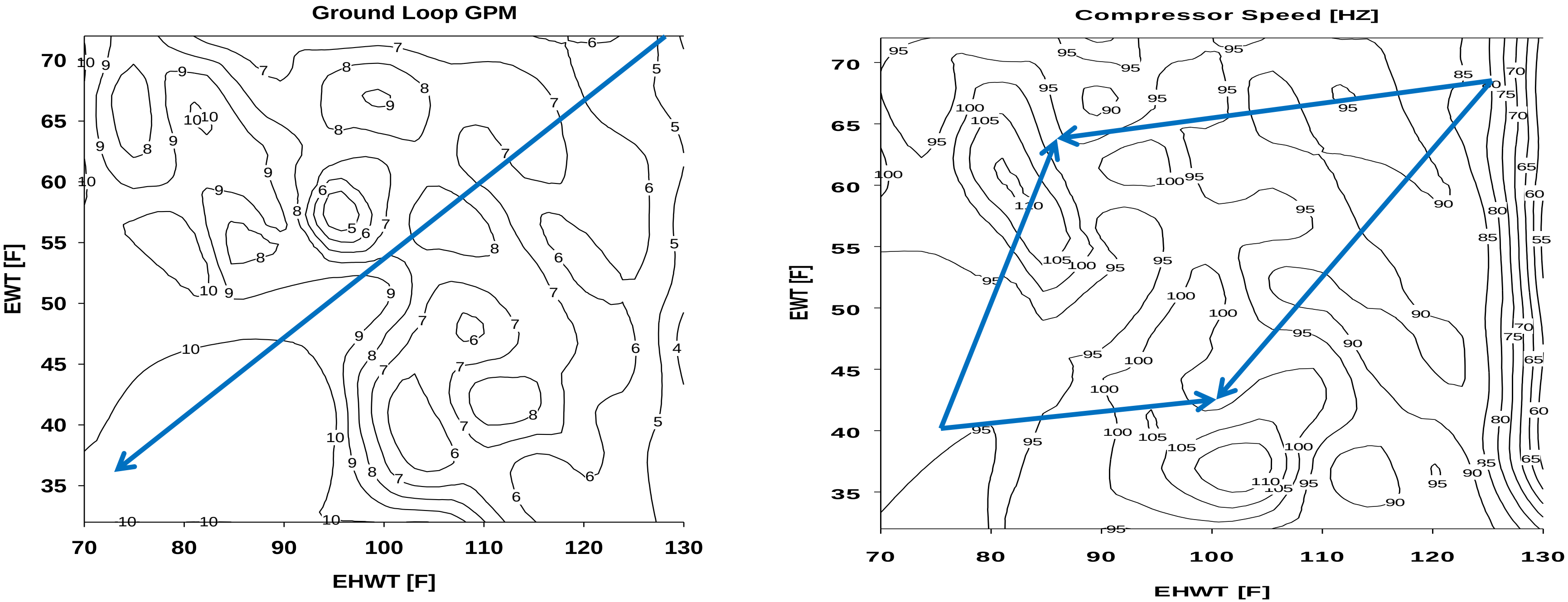


At left corner, HPWH can't control T_supply = 135°F @ 1.0 GPM minimum WH flow rate



2.7.1 Developing Control Functions

Curve-Fit Adjustable Variables to Develop Control Functions

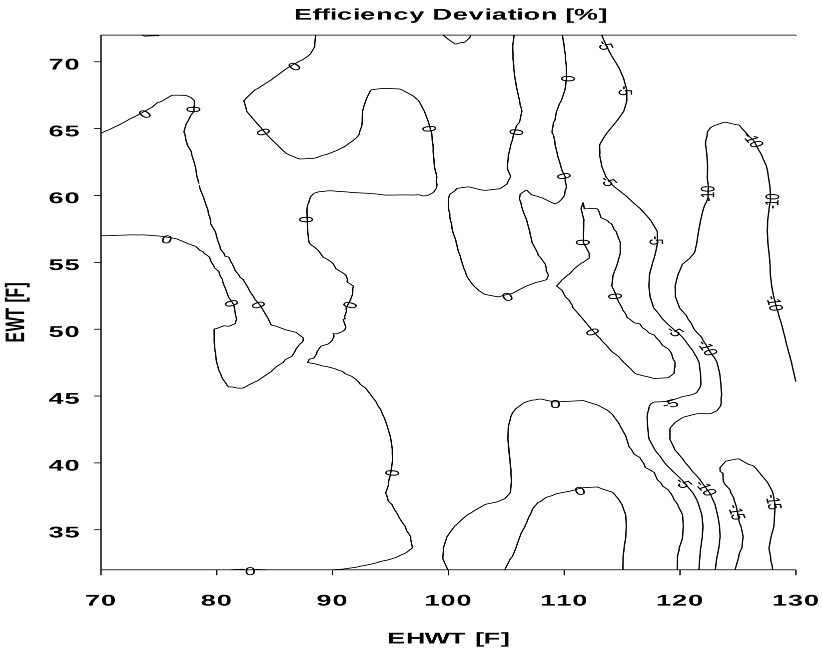


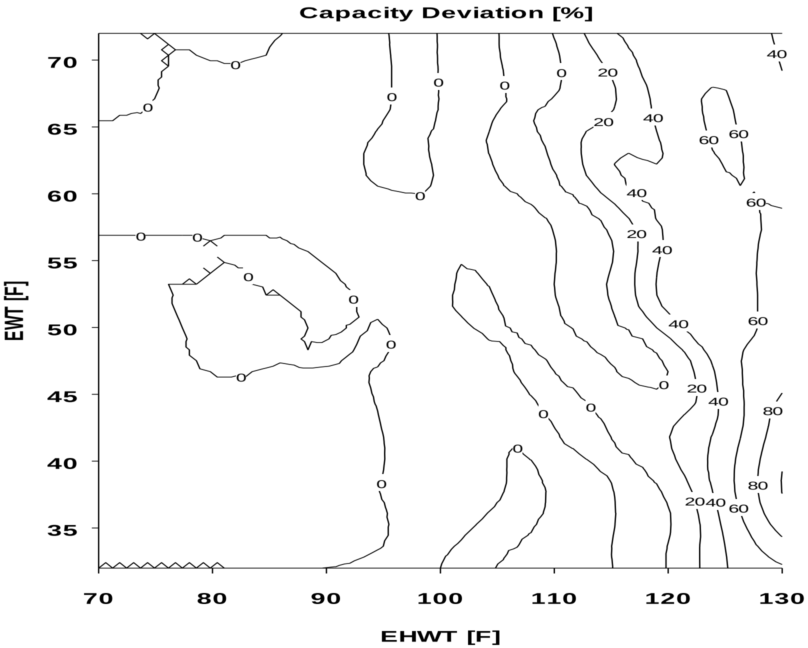
- Required ground GPM and compressor speed increase with reducing EWT and EHWT.
- Can't run max compressor speed (120 HZ) @ low EWT as this drops T_sat_suc below the min 20°F constraint.

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.