David Sellers

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Modeling Perfection

BY DAVID SELLERS, P.E., MEMBER ASHRAE

I've been thinking about changes since the olden days when I learned predictive energy modeling. The state of the art then was a blunt instrument compared to current methods. Yet, challenges still exist correlating the model to a reality that doesn't exist. This column shares some techniques I use to assess chilled water plants to inform better plant staging/optimization strategies and/or equipment selection.

Because my career evolved to focus on existing facilities, my modeling has become forensics-oriented and spreadsheet-based. The spreadsheets are not intended to calculate the building's resource consumption; the building tells us that. Rather, they use utility/trend data to provide a hypothetical picture of what might be possible in a somewhat perfect world.

The Existing Building Commissioning (EBCx) Angle

A subtle difference exists between applying models for design/new construction projects vs. existing building projects. In the former, the model is informing design decisions and/or demonstrating compliance with codes or building certification programs.

In the latter, the model helps you understand why the facility is *not* meeting the design target, correct the issues identified, adapt it to the current operating profile or program and take things to the next level in terms of sustainable, efficient operations.

One benefit associated with an existing building is that you have utility and trend data to model with. But for many EBCx practitioners, there can be constraints.

1. There may not be a calibrated model of the facility or it may be constrained by the algorithms contained in the calculation engine behind it.
2. The budget/timeline may not support modeling.
3. Many practitioners are passionate about building efficiency, proficient with spreadsheets, familiar with HVAC fundamentals, and willing to learn. However, they may not have a design background and may find the level of rigor required to develop an energy model intimidating and/or beyond their expertise.

The good news is that *the building knows the answer* and can tell us how well it is performing, how it is using resources and where its issues are via its trend data. Armed with this information and spreadsheets, we can compare the data with what we think should happen in a perfect world to guide our efforts.

Complementing the analysis are field observations documenting the equipment operating state/physical configuration and performance data procured from documentation and field tests.

The diagnostic tool (spreadsheet) I will use as an example applies a simplistic relationship between outdoor air temperature (OAT) and cooling load to identify deviations from what might be expected given the physics of the system and facility.

The technique may not meet the rigor associated with a true investment-grade model. But, in my experience, the information provided can be used to make investment decisions for resource efficiency and optimization projects—decisions based on the physics of the systems

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and their real-time interactions with the occupants and climate.

It's All About the Load Profile

The models I cut my teeth on ran on bin weather data algorithms due to the available computer technology, which involved a machine as big as a house at a remote location—a crude approach by today's standards. But crude as they were, they provided insight into the load profile, and that information is golden.

It's one thing to select/configure equipment to handle the design condition in an efficient, repeatable, reliable and robust manner. It's an entirely different—and far more critical—thing to select/configure the equipment to deal with the nuances of the load profile.

Therein lies the challenge (and I would suggest, the joy) of our occupation.

Cooling Load, Cooling *Coil* Load, And Outdoor Air Temperature

If you asked the "average person" if cooling load was related to OAT, they'd probably say "absolutely." But if you work with complex buildings, you know there is a lot more to it.

An eye opener for me early in my career came on a sunny but wintery (5°F [–15°C]) St. Louis day when I realized that without cooling, the core of the high-rise I was troubleshooting would overheat.* Clearly, the core load was related to more than outdoor air temperature.

I subsequently realized that:

- The *coil load* (vs. space load) is very much tied to the OAT;
- For a 100% outdoor air (OA) system, the coil load *is* an OAT load; and
- Integrated economizer-equipped systems *are 100% OA loads* much of the time.

Granted, space and coil loads are related:

- The space sensible heat ratio (SHR) likely set the coil leaving conditions.
- For variable flow systems, the sensible gains in the space will drive the flow profile.

But, if you gain a sense of the flow profile for a system (using trending or engineering judgement) and determine the coil's design performance metrics, you can understand a lot about the design intent, space loads, ventilation loads and how the system would use resources if it were functioning as intended. Comparing that to reality allows you to identify issues (aka opportunities).

Cooling Coil Insights

You can deduce a lot from cooling coil performance specifications. Ideally, you will find them on a drawing or equipment submittal. Failing that, other options include using a coil program to build a geometrically similar model of your coil, and/or functional testing.

Minimum Outdoor Air Percentage

For an economizer-equipped system, the cooling coil is typically selected for the design flow rate on the design day with the system using minimum outdoor air (MOA) percentage. The entering air condition represents the result of mixing return with outdoor air and will be proportional to the MOA flow and the properties of the two airstreams.

In EBCx, uncertainty can exist about what the original design conditions were. But if you plot the return condition and coil entering condition on a psych chart and project a line through those points, the design condition should lie on that line.

You can contrast known ASHRAE conditions with your projection. In a perfect world, the line will intersect one of them. In an imperfect world it won't, but it will come close enough to one to allow you to make an informed decision about the designer's thinking.

From there, you can project the MOA percentage (*Figure 1*) or deduce it mathematically (*Equation 1*.†)

$$\%_{\text{Outdoor Air}} = \frac{\left(t_{\text{Mixed Air}} - t_{\text{Return Air}}\right)}{\left(t_{\text{Outdoor Air}} - t_{\text{Return Air}}\right)}$$

$$\%_{\text{Outdoor Air}} = \frac{(78.2 - 73.0)}{(93.8 - 73.0)} = 0.25\ (25\%)$$

Having established the design OA and MOA conditions, you can use similar techniques to "mine" the coil performance for additional information. One thing will lead to the other, starting with the ventilation load, the total

*The operating team had disabled economizers to keep coils from freezing due to poor mixing design.

†Derived at "Economizers–The Physics of a Mixed Air Plenum." https://tinyurl.com/OAPctDerived

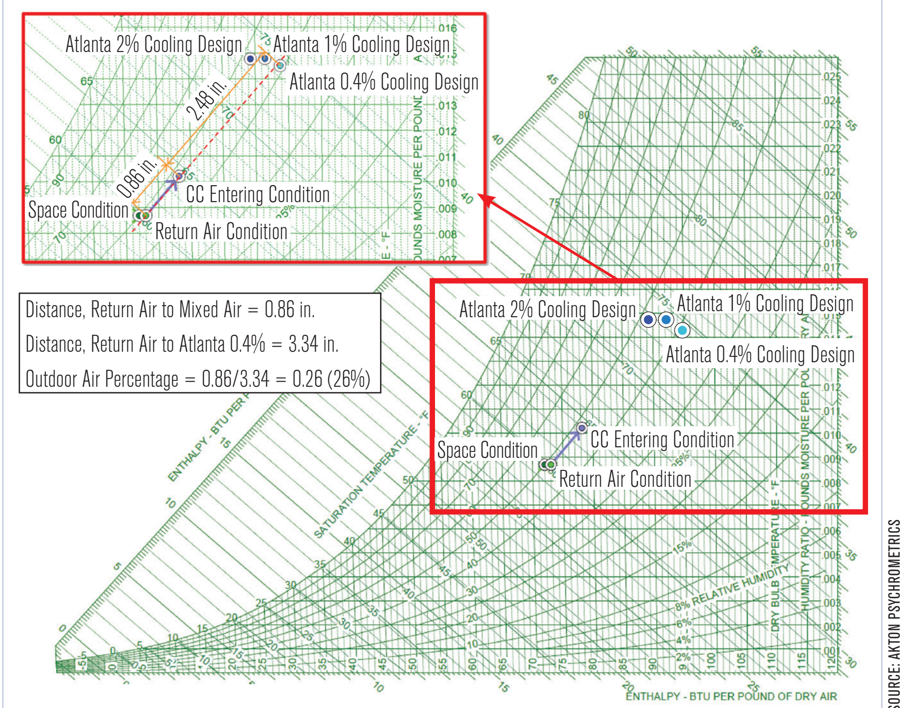
space load, the space sensible and latent loads‡ and the SHR.§

The Perfect Chilled Water Load

The Concept

Having discussed insights gleaned from coil specifications, I will now focus on gaining insight into how a system and the plant serving it are working by considering what would happen to the load as the OAT changed and by (literally) drawing a picture of it. *Figure 2* illustrates this for a plant serving a cooling coil in an integrated economizer-equipped AHU (*Figure 2a*) and a 100% OA AHU (*Figure 2b*).

FIGURE 1 Using a psychrometric chart, you can graphically determine MOA percentage for an Atlanta air-handling system.



OAT Below Design Leaving Air Temperature

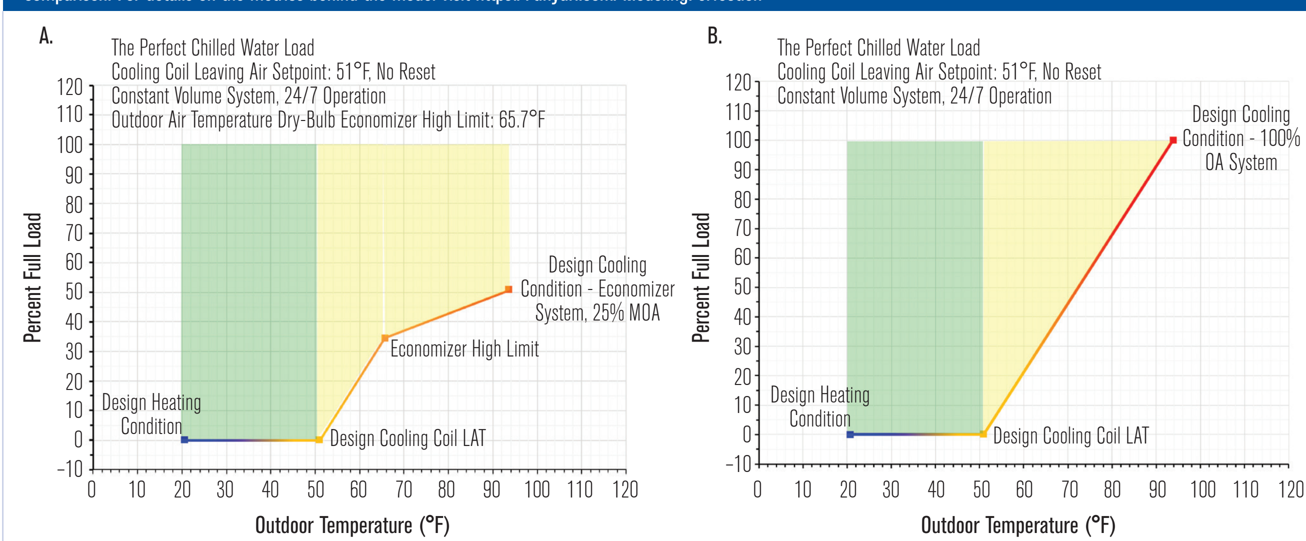
For both systems, when the OAT is below the design leaving air temperature (LAT), mechanical cooling isn't required. Even though there is a legitimate load in the area served—perhaps a near design load—it is handled by outdoor air.

OAT Above Design LAT

As the outdoor temperature rises above the LAT setpoint, both AHUs require mechanical cooling to supplement the cooling provided by OA. But the load on the coil is an OA load.

Because of the integrated economizer, the economizer-equipped system operates as a 100% OA system. But the mechanical cooling load is generally less than it would be if

FIGURE 2 The perfect chilled water load for a coil in (a) an integrated economizer AHU and (b) a 100% OA AHU. 100% load = 100% OA load for both charts to allow direct comparison. For details on the metrics behind the model visit https://tinyurl.com/ModelingPerfection



‡Some spaces may have code-driven air change rates setting the flow rate. Thus, the result of applying this technique may include reheat.

§This assumes the SHR line intersects the saturation line, which may not be true for spaces with low SHRs; keep this in mind when applying this technique.

the system was handling return air mixed with the MOA.

OAT Above Economizer High Limit Setpoint

When the outdoor air temperature reaches the high limit setpoint, the economizer-equipped system should revert to MOA. From this point forward, the coil load is tied to the space load because the space heat and humidity will be recirculated and mixed with the MOA.

In contrast, the load on the 100% OA system will always be divorced from the load in the space (although it will likely be numerically equal at some point). But the coil will never see the heat and humidity generated in the space, just the outdoor air heat and humidity.

Economizer High Limit

A crucial parameter associated with a working economizer is the high limit setting used to terminate the economizer process and revert to MOA. The exact setting will vary with climate and the nature of the load.

Ideally, it should be the outdoor air condition where the amount of energy required to cool 100% OA is exactly equal to the amount of energy required to cool the mixed airstream operating on MOA. Achieving that is not as simple as it sounds.

Energy codes will provide a recommended setting for a given climate zone. While there are quite a few strategies that can be used, it has been demonstrated that the OA dry-bulb strategy tends to be the best option.[#]

That is the approach I typically use, but I like to fine-tune it, as illustrated via the link included with *Figure 2*.[II]

Concept Application

Applying this concept requires OAT and cooling load data, which can be obtained via trending and functional testing. The data is then superimposed on the perfect system lines as a scatter plot. If everything is perfect:

- The data cloud will follow the perfect lines.
- There will be scatter around the perfect lines due to sensor accuracy and factors other than OAT that drive the load.
- Data points that stray into the areas highlighted in green or yellow in *Figure 2* may represent opportunities to improve performance and/or save resources.

To demonstrate this, I will use a spreadsheet that takes the model of perfection to the next level using:

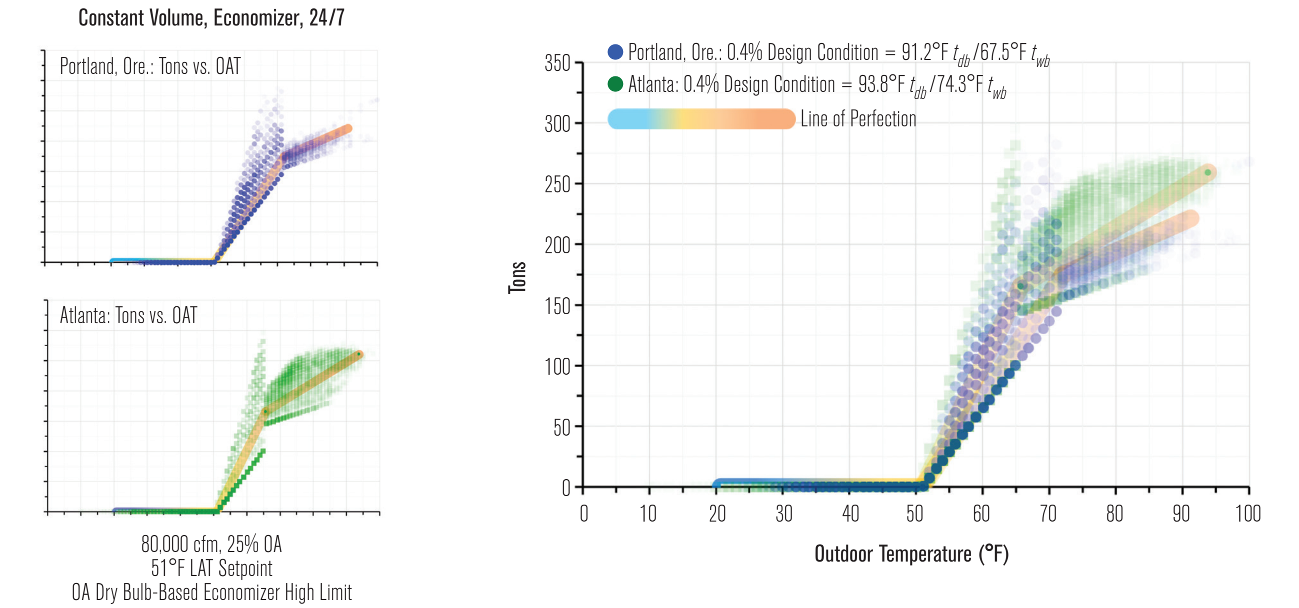
- Hourly weather data;
- Cooling coil performance metrics;
- Design conditions;
- Psychrometrics;
- Fundamental HVAC equations; and
- Logic.

I will use it to project a coil load for each hour in the weather data file. The output is superimposed on the lines of perfection, creating a "cloud" providing additional insight.

[#]See "Economizer High Limit Controls and Why Enthalpy Economizers Don't Work," https://www.cmfnh.com/documents/ASHRAE_Journal_QA.pdf

[II]See Chapter 3 of the "Functional Testing Guide-Air Handling System Reference Guide." https://tinyurl.com/FunctionalTestingGuide

FIGURE 3 The perfect load for an integrated economizer-equipped AHU in Portland, Ore., contrasted with an identical unit in Atlanta.



Looking for Shapes in the Clouds

As a proud member of the Cloud Appreciation Society,** I whimsically look for shapes in atmospheric clouds. But that same fascination serves me well in my "day job" because data cloud shapes can be revealing.

For example, in *Figure 3*, the steepness of the inclined line of perfection and the data scatter that exists around it is affected by the climate.

Note the difference in the pattern created by the much more humid Atlanta environment relative to Portland, Ore., even though the design dry-bulb temperatures are within 2.6°F (1.4°C) of each other.

A dense cloud correlates with many hours at a given tonnage and OAT (many "dots" plotted on top of each other). A barely visible cloud correlates with very few hours at those conditions.

Figure 4 illustrates how common operating variables impact the cloud shape. By comparing *Figure 4a* with the other charts, you can see how moisture (*Figure 4b*), economizer high limit settings (*Figure 4c*), VAV operation (*Figure 4d*) and schedules (*Figure 4e*) manifest themselves.

Figure 5 illustrates using this approach for a plant serving a hypothetical 200-room full-service hotel with:

- Economizer-equipped VAV systems;
- Constant volume (CV) makeup air unit systems (MAUs),
- Fan coil units serving the guest rooms; and
- Chilled water-cooled ice machines and walk-in coolers.

**There really is one: https://cloudappreciationsociety.org/

Key Takeaways

- The cloud created by the variables in *Figure 5* follows the lines of perfection.
- The variables introduce data scatter.
- The base load shifts the horizontal portion of the perfect cloud upward.
- The transitions from horizontal to an incline are the result of the OAT exceeding system LATs.
- The change in the slope at warmer temperatures is the result of the economizer high limit. This is more apparent in *Figure 5b* (the inset is the economizer system cloud, isolated by filtering).
- For a given climate and high limit setting, the slope of the economizer portion of the cloud when operating on MOA is related to the MOA percentage, outdoor design conditions and high limit settings.
- Variable flow and schedules create bands correlating to those drivers.

The Clues

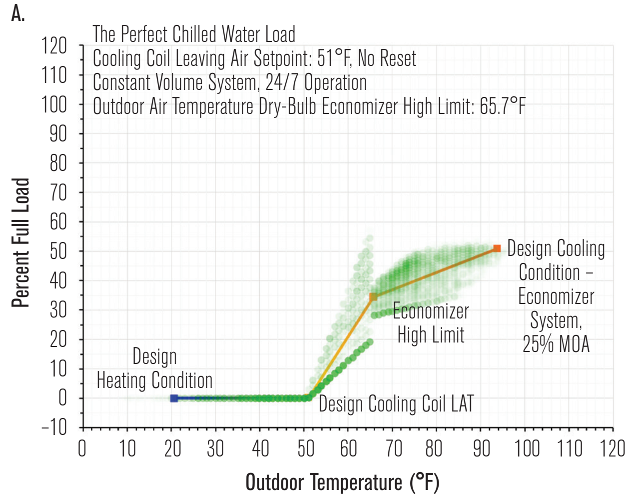
For a real facility, deviations from the perfect cloud are indicators of opportunity.

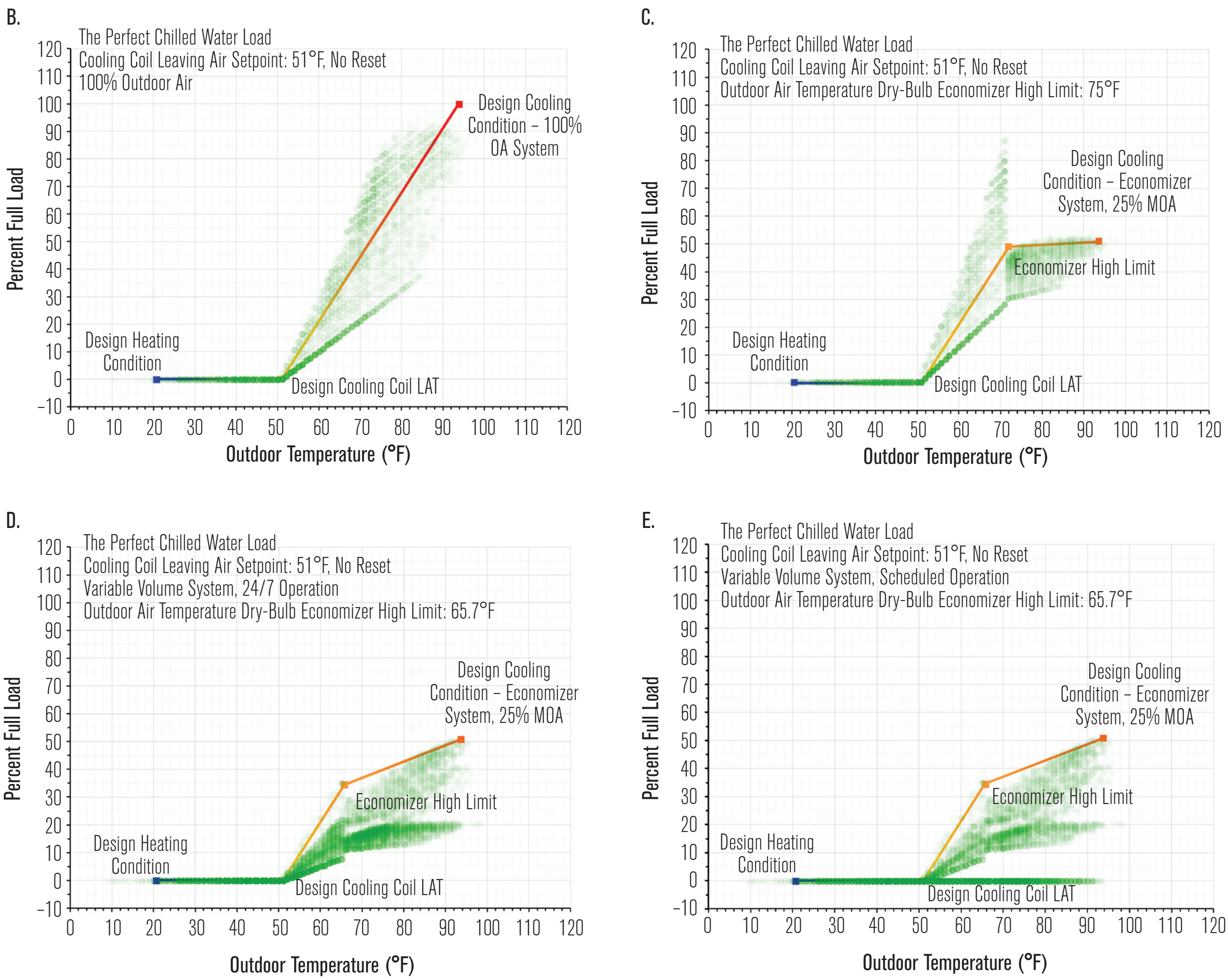
- Data points in the green and yellow areas in *Figure 2* indicate the potential to improve the use of OA cooling.
- A base load that deviates from known loads requiring year-round cooling often correlates to unnecessary preheat.
- A facility with alleged schedules and VAV systems that does not show distinct bands in the cloud may have

FIGURE 4 The impact of different operating variables on the shape of the perfect load lines and cloud.

A. Economizer-equipped constant volume system and **B.** 100% OA constant volume system operating as intended.

- **A.** vs. **B.** illustrates the impact of moisture for an economizer-equipped system vs. a 100% OA system operating at a constant volume, 24/7.
- **A.** vs. **C.** illustrates the impact of setting the economizer high limit too high.
- **A.** vs. **D.** illustrates the impact of VAV operation vs. 24/7 constant volume operation.
- **A.** vs. **E.** illustrates the impact of VAV operation plus a schedule vs. 24/7 constant volume operation.

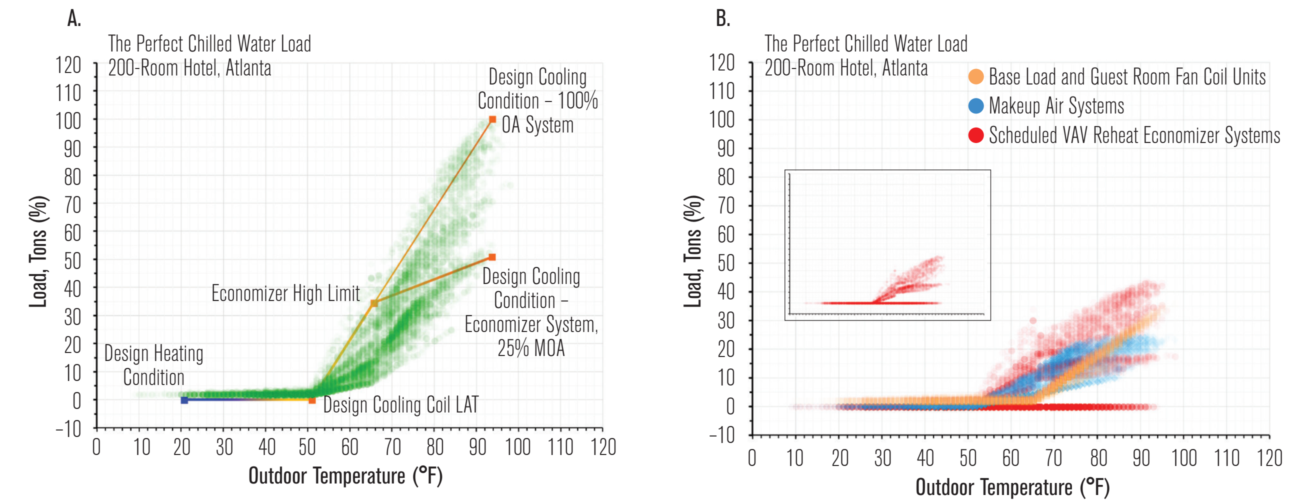




scheduling or flow management opportunities.

- If there are economizers but no "bend" in the data cloud in warm weather, then the economizer high limits are suspect.
- A flat (vs. inclined) cloud above the economizer high limit setpoint can point to under-ventilating or incor-

FIGURE 5 The Perfect Chilled Water Load, 220-room hotel, Atlanta. The cloud in (a) is the sum of the clouds in (b). Figure 5b illustrates the individual clouds generated by the different load types.



rect economizer high limit setpoints.

An Example of Perfection vs. Reality

The facility behind our example shown in *Figure 6* is a full-service, 620-room hotel in Atlanta. It has a mix of constant volume 100% OA systems and VAV reheat economizer systems. It has approximately 70 tons (246 kW) of 24/7 cooling load without access to outdoor air, and air-cooled ice machines and walk-in coolers.

Advertisement formerly in this space.

Scheduling and Variable Flow Opportunities

The area inside the green outline in *Figure 6b* has no bands in it. This suggest that VAV systems are not varying flow and/or that schedules are not implemented. Moving into the project, we encountered both opportunities.

Ventilation and Economizer High Limits

"Eye-balling" a line through the dense part of the cloud (red line, *Figure 6c*, *Figure 6d*, *Figure 6e*) reveals a flatter slope than the perfect line in *Figure 6c* (compare the yellow line with the red line). When the perfect lines are adjusted to reflect 0% MOA in *Figure 6d* (compare the slope of the orange line in *Figure 6c* and *Figure 6d*), there is much less of a difference in slope (*Figure 6d*). Thus, underventilation is a possibility.

However, the slope mismatch can also be an indication of an inappropriate economizer high limit setting. Since we are dealing with a cloud rather than a line, the inflection point where the cloud shape becomes more horizontal is over a range of temperatures: 68°F to 72°F (20°C to 22°C)—the green and purple lines in *Figure 6e*.

The perfect lines in *Figure 6a* to *Figure 6d* were set assuming an OA dry-bulb economizer high limit of 65.7°F (18.7°C), which is appropriate given the Atlanta location and the indoor design target (*Figure 2* and

FIGURE 6 **Plotting Real Data Against the Lines of Perfection. The blue cloud represents a year of hourly tonnage data. The column text discusses the details of the issues highlighted.**

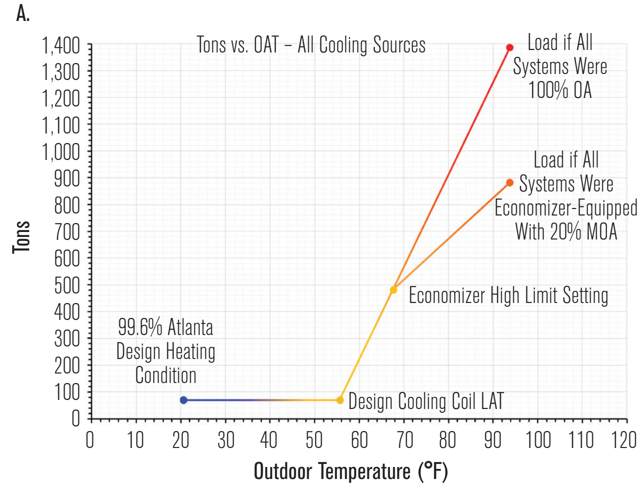
A. The lines of perfection.

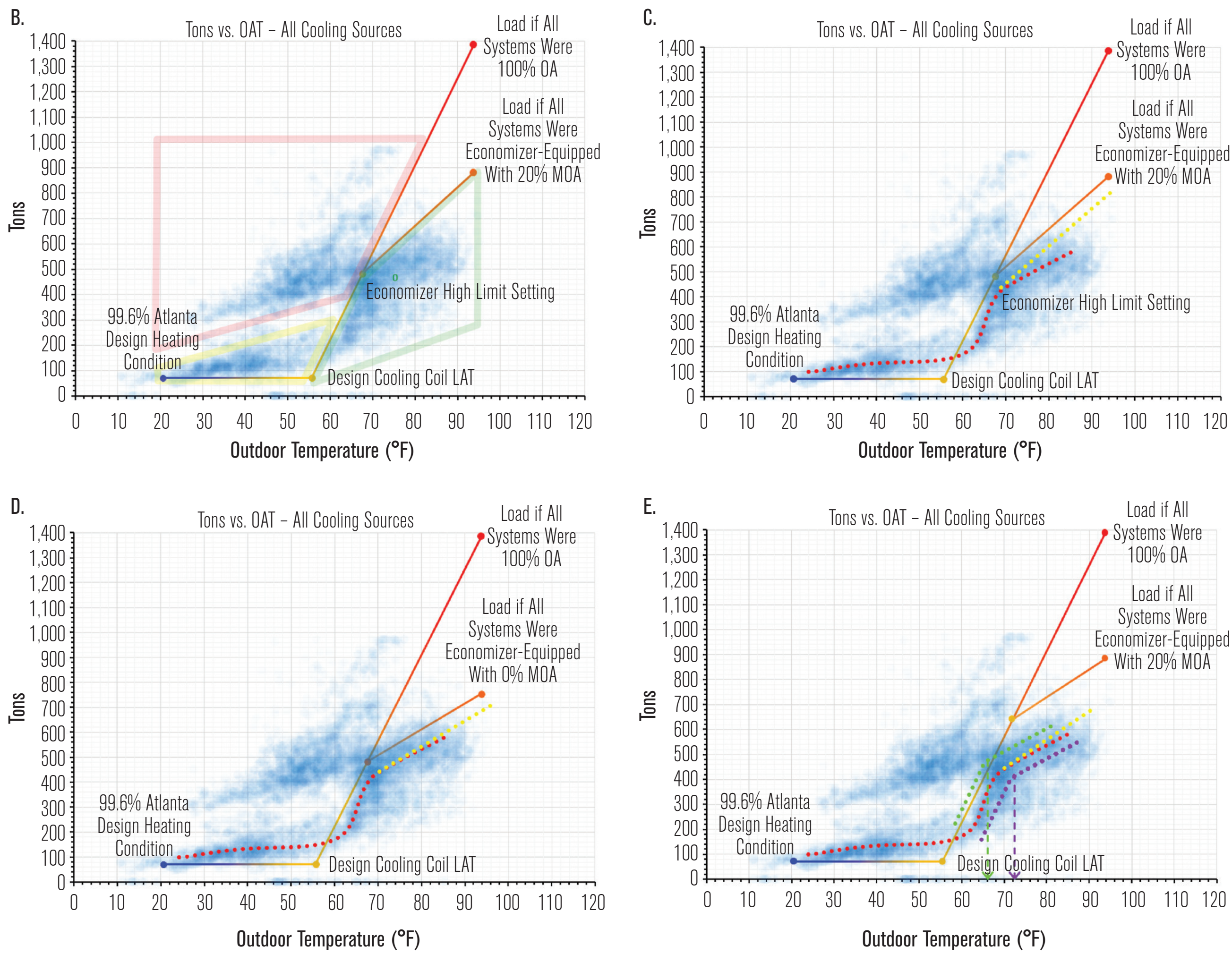
B. The cloud with opportunity areas highlighted in red, green and yellow.

C. Yellow dots vs. red dots vs. orange line slope reveal economizer issue.

D. Yellow dots vs. red dots vs. orange line slope reveal a potential under-ventilation issue.

E. Purple dots and green dots vs. the lines of perfection reveal a potential economizer high limit issue.





discussed at https://tinyurl.com/ModelingPerfection). Our cloud suggests that the transition to MOA occurs at this value some of the time (the green lines), but not always (the purple lines).

If we adjust the perfect lines to reflect a setting of 72°F (22°C) (*Figure 6e*), the slope comes into general agreement with the data cloud. Thus, it is also possible that the economizer high limit settings need some attention.

FIGURE 7 Filtering the data cloud to project the savings potential associated with eliminating the unnecessary operating hours.

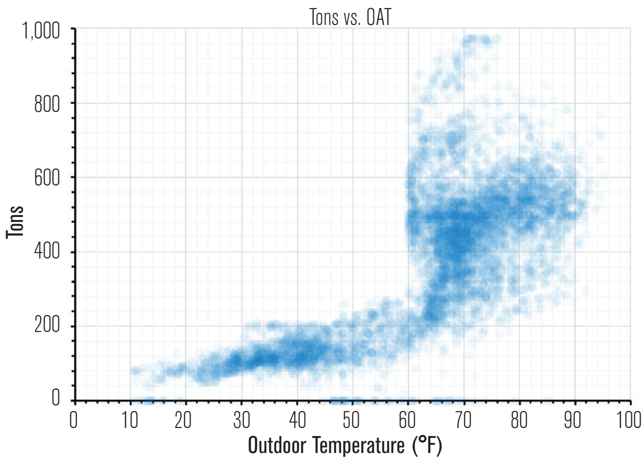


TABLE 1 Potential savings for eliminating false loads.

		TOTAL OBSERVED TON HOURS 3,369,098
ITEM	LOW END	HIGH END
Nominal kW/ton	0.50	0.90
Nominal Electric Rate	$0.0800	$0.1000
Annual kWh	1,684,549	3,032,188
Annual Cost	$134,764	$303,219
False Load Ton Hours	918,609	(27% of the Total)
Annual Unnecessary kWh	459,304	826,748
Annual Unnecessary Cost	$36,744	$82,675

Not an Exact Science

The good news is that the diagnostic model clued us in to potential ventilation and economizer optimization opportunities. But by its nature, it could not tell us for sure which problem existed.

However, it did focus us on the economizer-equipped systems, where we found that both opportunities existed (with a unique twist that will have to wait for a future column for discussion).

Dots Where None Should Exist!

What jumps out the most in *Figure 6* is the concentration of dots in a place you would not expect them.

Dots in the areas outlined in red and yellow (*Figure 6b*) are in places where the facility should have been able to handle the cooling needs using outdoor air. Their existence points you toward the potential for issues with economizers (red area) and preheat (yellow area). As we moved into the project, opportunities were identified in both areas.

Dots Have Value

The dots represent ton hours. By filtering the spreadsheet, we can add them up. *Figure 7* illustrates what is revealed by doing that for the ton hours inside the red outline in *Figure 6b*.

While broad by design, the projected savings are eye catching and founded on the physics of the building and its systems as revealed by trend data and operating parameters early in the project.

This technique allowed us to firm up savings projections and budgets initially based on more rudimentary data and industry metrics.[††] We were working with a director of engineering and crew who had just inherited the facility. This information focused their efforts to turn things around, including selling management on what they needed to succeed.

The Perfect Economizer

A similar technique can be used to model a perfect economizer. Since the results of our analysis pointed to economizer and preheat issues, we used it to further validate the savings we identified.

Conclusion

With a bit of ingenuity and a sense of what should be going on, EBCx practitioners can leverage data to identify and quantify operating issues, without being full-fledged designers/modelers. The information can also be used to ensure the benefits persist and identify other opportunities.

Acknowledgments

Thanks to my fellow Engineer's Notebook columnists for their thoughtful review comments and insights; Sabastian St. John /St. John Consulting for support in capturing the data in the example; Jay Tulley and Brian Clark at CERL and John Hanes at Dewberry for their support of the perfect load and economizer concepts as I worked with them on a tool they are developing; Keith Shockey for sharing his data and his relentless pursuit of improvements. ■

[††]See "Developing Retrocommissioning Implementation Budgets; Establishing the Big Picture" at https://tinyurl.com/BigPictureEBCxSaving