
David Sellers

The Perfect Economizer

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My previous column* in the October 2021 issue of *ASHRAE Journal* explored a technique that compares a chilled water plant's performance to perfection (*Figure 1*). Data from a near-perfect plant will create a cloud around the solid lines if plotted against them. A hazy blue cloud nowhere near the lines, like the areas outlined in red, yellow and green, indicates a potential problem. A common reason for the unnecessary chilled water use in the areas outlined in red and yellow is dysfunction in the preheat and economizer processes. Thus, the team I was working with at the facility decided to use a similar idea that I call "The Perfect Economizer Concept" to assess their air-handling units (AHUs).† That analysis technique is the focus of this column.

Nothing New

The "Perfect Economizer" concept is similar to the "Perfect Load" concept from my last column in that you create a chart that illustrates perfection and then plot real data against it to see how closely reality matches it.

The idea is not particularly new. For example, the (free) Universal Translator application§ includes a module that uses this approach.

This column will illustrate how the concept works, and how it can be used to perform diagnostics founded on field data. If I am successful, you should be able to take what I write and build a spreadsheet in Excel or similar application that will perform the analysis.# When I first started using this approach, we did the math with paper, pencil and calculator using a handful of manually measured data points. The evolution to computers has opened the door to much more powerful data visualization capabilities.

The analysis bottom line is based on how well the system in question mixes outdoor air (OA) and return air (RA) relative to a theoretical requirement for mixed air (MA), i.e., "perfection." It is important to recognize that while mixing is a key goal for an airside economizer, there are other important, related processes, including minimum outdoor air (MOA) regulation, integration with mechanical cooling, preheat, humidification and dehumidification, and building pressure control.

The technique will flag issues with MOA percentage and preheat and cooling integration but does not directly address building pressure control. Dehumidification and humidification integration are somewhat addressed by the various settings used to define the inflection points in the lines of perfection.

*"Modeling Perfection" *ASHRAE Journal*, October 2021.

† As a clarifying point, I am going to focus on a perfect airside economizer. But the fundamental principles can be extrapolated to waterside economizers.

§ https://tinyurl.com/UTranslate

For those who would like a starting point, you can download the spreadsheet behind the images in the article at https://tinyurl.com/PerfectEconomizer

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FIGURE 1 Perfection vs. reality for an Atlanta hotel chilled water plant. Tons vs. OAT–all cooling sources.

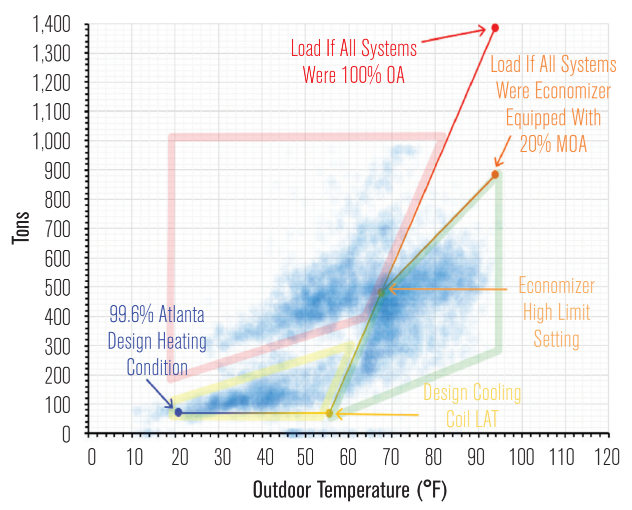
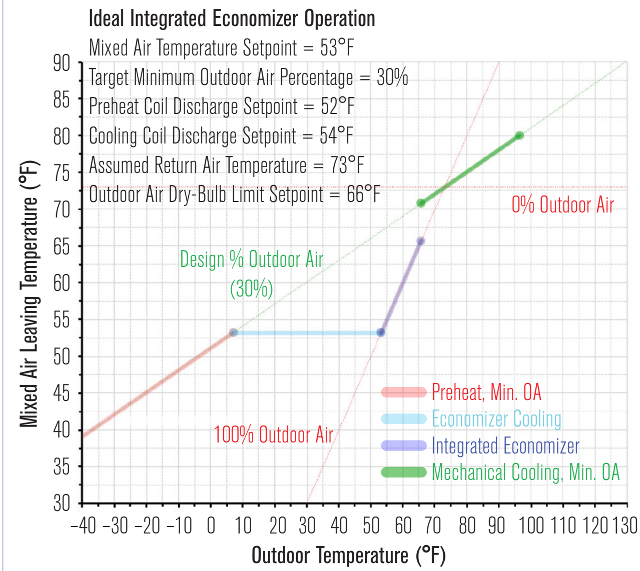


FIGURE 2 OAT vs. MAT for a perfect economizer.



What Makes an Economizer Perfect?

Airside economizers are based on a simple concept: it's cool outside, and we need cooling in the core of our facility, so let's use the cool OA to do that instead of mechanical refrigeration. Designing and operating a system so it can successfully do that is challenging because of all the variables in play, especially in an extreme climate.

Kelley Cramm's recent column "Why Don't Mixing Boxes Mix and What Should We Do About It?"[||] includes several case studies that illustrate the challenges and solutions. It also includes a great reference list citing many of the classics on the topic.

At the end of the day (building pressure control set aside), success can be judged by how well the system delivers the design MA temperature under all operating conditions. The approach we will discuss compares a plot of actual OAT vs. MAT data for a system with lines that show what that data would look like if the economizer was functioning perfectly (*Figure 2*).

To create the lines of perfection (hereafter called "the lines"), we need to define what would make an economizer perfect.[**] For the purposes of our discussion, those attributes include:

- *Accurate temperature sensing*, including adequate coverage of the entire mixed air plenum so temperature and velocity stratification are reflected by the sensors providing the data and controlling the process.
- *Accurate OA flow sensing* for systems where OA flow measurements are provided.[††]
- *Relative calibration with other sensors and freeze-stats in the system* to ensure that all control processes are "seeing" the same thing and that any temperature differences are true differences vs. differences created by the sensor accuracy specification and/or the differentials and hysteresis inherent in a mechanical operating mechanism.
- *Good mixing*, which is related to both the configuration and sizing of the dampers and the distance provided for mixing to happen.[‡‡]
- *Integration with other HVAC processes*, including MOA regulation, preheat, warm-up, heating, mechanical cooling, humidification, dehumidification and schedules.

[||] *ASHRAE Journal*, February 2020.

[**] For more details, visit https://tinyurl.com/PerfectEconomizerDetails

[††] For the existing, often older, systems I run into, this is surprisingly uncommon, even though it is a component of every sequence in Guideline 16 and required by ASHRAE 62 for decades.

[‡‡] One of the challenges designers face when using packaged or modular equipment is that the details of damper sizing and configuration are relegated to the manufacturer and constrained by the nature of their product line. One option providing the designer with a bit more control over this is to field-erect a mixing box based on the criteria/recommendations provided by ASHRAE Guideline 16-2022, *Selecting Outdoor, Return, and Relief Dampers for Air-Side Economizer Systems*, and the resources Kelley cited in her article. This also allows designers to provide some distance between the mixing box and the AHU, which, as Kelley illustrated, can do a lot of good.

- *Integration with the loads and climate* so that the economizer process is terminated when it no longer provides an energy-efficiency benefit. Calibration of the humidity sensors used to compute enthalpy and dew point is crucial here if you are using those parameters to manage the economizer process.§§

Visualizing Perfection

The Math

Figure 2 is based on the rate version of the steady flow energy equation for a mixed air plenum

$$\bar{Q} + \sum_1 \left[\dot{m} \times \left(u_1 + \frac{p_1 v_1}{J} + \frac{z_1}{J} + \frac{V_1^2}{2gJ} \right) \right] = \frac{\bar{W}}{J} + \sum_2 \left[\dot{m} \times \left(u_2 + \frac{p_2 v_2}{J} + \frac{z_2}{J} + \frac{V_2^2}{2gJ} \right) \right] \quad (1)$$

where

- Q = Heat in Btu/lb
- W = Shaft work, ft·lb/lb
- u = Internal energy, Btu/lb
- pv = Flow work; pressure in lb/ft^2 × specific volume in ft^3/lb, ft·lb/lb
- J = Mechanical equivalent of heat; 778 ft·lb/Btu
- V = Velocity in fps
- g = Gravitational constant, 32 ft/s·s

The bar over the Q and W terms ($\bar{Q}$ and $\bar{W}$) means that the heat transfer and/or work are being done at some sort of rate, like Btu/h or ft·lb/h, and the dot over the *m* term ($\dot{m}$) means a mass flow rate, like lb/h.

The Σ symbol means that the parameters inside the parentheses are totalled for all of the fluid streams on each side of the equation.

Fortunately, things can be made a bit less intimidating via simplifying substitutions and assumptions, resulting in very useful relationships (*Equation 2*, *Equation 3*, *Equation 4*, and *Equation 5*)##

$$\%_{OutdoorAir} = \frac{(t_{MixedAir} - t_{ReturnAir})}{(t_{OutdoorAir} - t_{ReturnAir})} \quad (2)$$

$$t_{MixedAir} = \left[\%_{OutdoorAir} \times (t_{OutdoorAir} - t_{ReturnAir}) \right] + t_{ReturnAir} \quad (3)$$

$$t_{OutdoorAir_{Mix32}} = \left[\frac{(32 - t_{ReturnAir})}{\%_{OutdoorAir}} \right] + t_{ReturnAir} \quad (4)$$

$$t_{OutdoorAir} = \left[\frac{(t_{MixedAir_{Design}} - t_{ReturnAir})}{\%_{OutdoorAir}} \right] + t_{ReturnAir} \quad (5)$$

The Picture

The equations and the economizer's design setpoints are used to "paint the picture." Data from a perfect system using error-free sensors and fixed setpoints and flows will fall *exactly* on top of the lines.

Data from a near-perfect real system will create a cloud around the lines and follow their shape. Deviations from the shape suggested by the lines are clues leading to opportunities to improve things.

This approach incorporates some simplifying assumptions. For example, it assumes that the return air temperature (RAT) is constant and that the MAT, cooling coil leaving air temperature (LAT), and preheat LAT setpoints are constant. Data from a real system will show scatter around the lines due to variations in these parameters.

Scatter will also be caused by system instability, sensor accuracy and hysteresis, actuator hysteresis, operator overrides and schedules. You can use Excel filters to eliminate scatter due to schedules. But it is worth looking at the data first because the pattern during those hours can reveal issues with damper seals or operational interlocks with valves and dampers.

One can also add spreadsheet features to accommodate things like reset schedules. But once you understand the analysis technique, you can use engineering judgement to discern "normal" scatter from an issue.

Setting the Stage (*Figure 3*)

The lines have their foundation set by basic economizer parameters including the MAT setpoint, the MOA percentage, an assumed RAT and an OA dry bulb high limit.‖‖

§§ If you want to get a sense of the challenges associated with this, the report from the National Building Control Information Program on humidity sensors is insightful: https://tinyurl.com/NBCIPReports

The derivation of these relationships can be found here: https://tinyurl.com/MAPlenumPhysics. *Equation 4* is a special case of *Equation 5* that tells you how cold it must be outside to create freezing mixed air. If you have not considered this in your design, you may experience a significant emotional event related to the phase change that water goes through at that temperature.

‖‖ The analysis uses an OAT dry-bulb limit. Systems using a different parameter like enthalpy or RAT can still be modeled by selecting an OAT high limit that would be appropriate for the system in question if that strategy was used. For example, if the system compared RAT to OAT and reverted to MOA when to OAT was greater than the RAT, setting the high limit value to match the average return air temperature will work.

FIGURE 3 Setting the stage.***

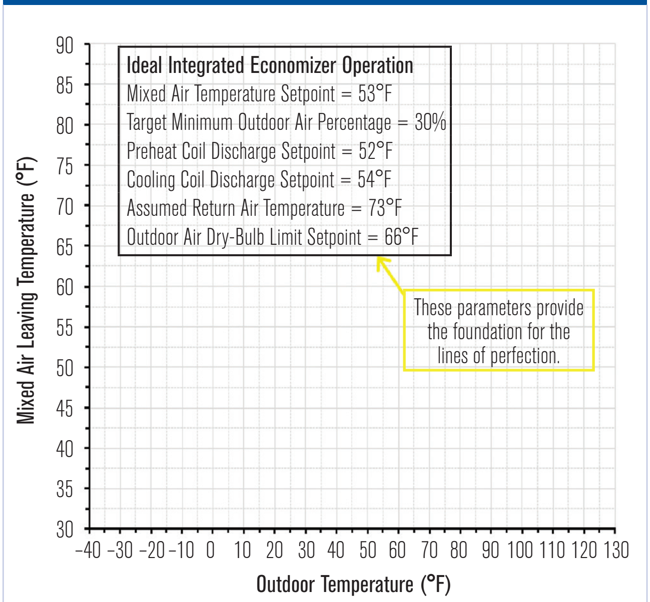
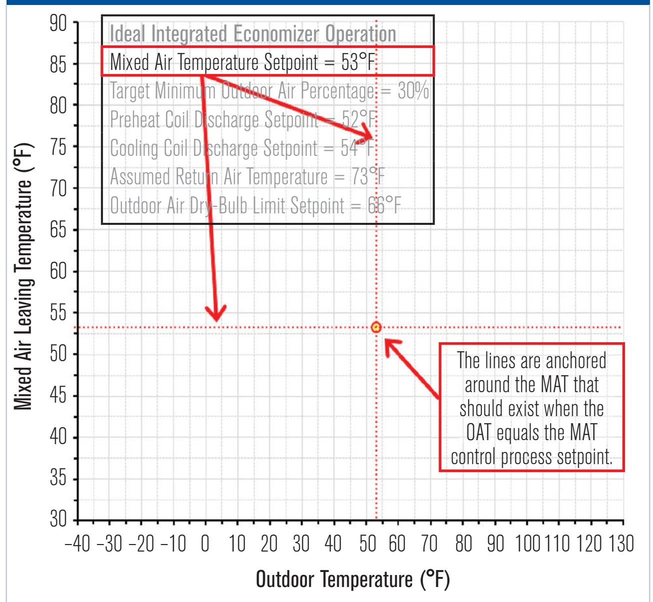


FIGURE 4 The starting point.



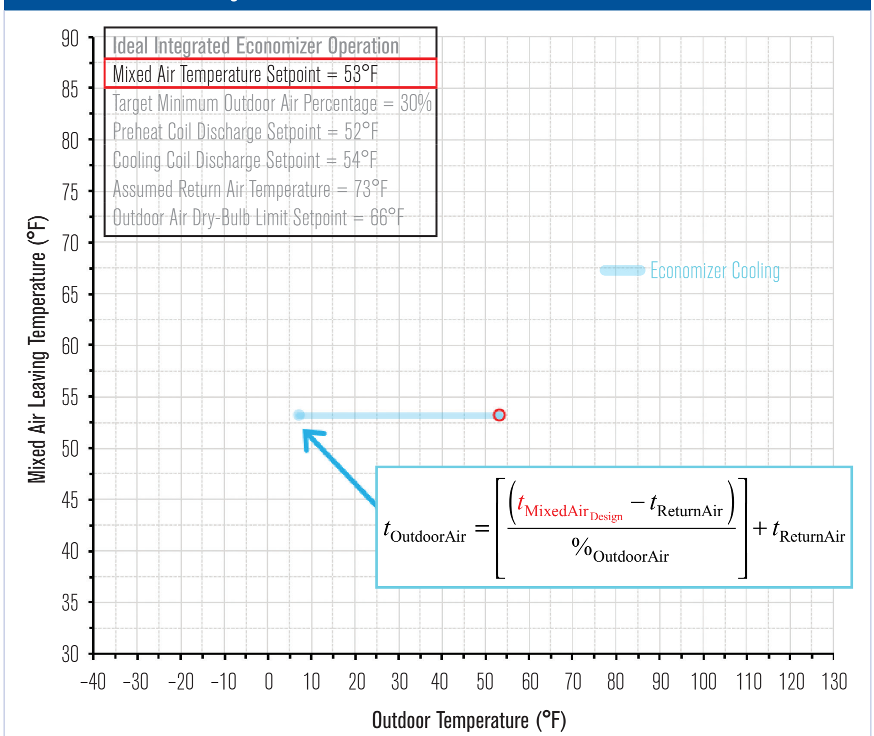
While the lines are focused on MAT, my spreadsheet includes features that show preheat and mechanical cooling operation if the data is available, which is why these setpoints are specified. This allows logic in the spreadsheet to model systems that use independent control loops for each process. A system that uses the cooling coil LAT to sequence everything is modeled by setting all the setpoints to the same value.

The Starting Point (*Figure 4*)

We can start the lines with an obvious condition: the mixed air temperature that should exist with the system operating on 100% OA. Our example will use 53°F (12°C).

At this condition, the OAT should equal the MAT, *unless*, for example, the return air damper blade seals are leaking. When you plot real data and see the cloud start to grow upward as the OAT approaches this point, the cause could be leaking RA damper seals.†††

FIGURE 5 Economizer cooling.



*** Some may observe that ASHRAE Standard 90.1-2019 would require a 65°F economizer high limit setting in the climate zone used in this example. I discuss the reasons this limit was not used in one of the blog posts referenced in endnote**.

††† Damper seals can leak for several reasons. The obvious one is that they are missing or torn up due to wear and tear. But for seals to perform, they need to be compressed. Most manufacturers include a torque requirement in their leakage specification. As a result, if insufficient torque is applied, either due to the capability of the actuator or the interaction of the linkage system, actuator crank arm and jackshafts, then perfectly fine blade seals may fail to perform because they are not fully seated or compressed. Visit https://tinyurl.com/ActuatorLinkagePhysics for details.

Economizer Cooling (*Figure 5*)

As the outdoor temperature drops below the design mixed air temperature, a perfect economizer will reduce OA flow to (but not below) the minimum requirement and increase RA flow to maintain setpoint. The MAT will hold constant as the OAT changes, creating a straight line on our chart.

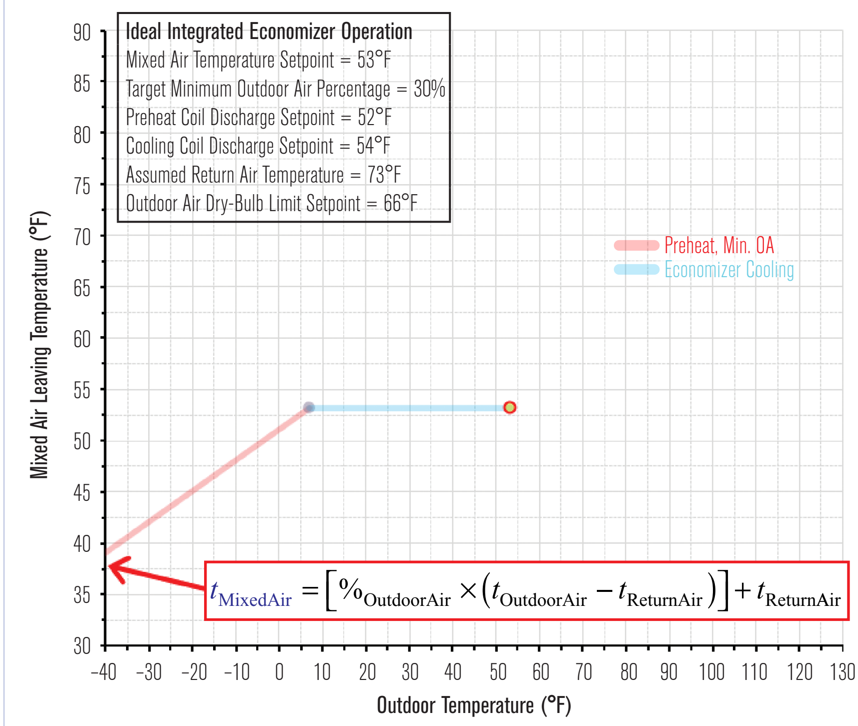
Two points define a straight line. In this case, the first point is the 100% OA point discussed above. The second is associated with the condition where the economizer dampers modulate down to the MOA position due to low OATs. We can calculate this temperature using *Equation 5*.

Data from a real system should create a cloud that follows the line in this area if things are working properly. However, there are some "normal" processes that could impact the shape a bit. For example, if there is a reset schedule that raises the supply air temperature (SAT) as OAT drops, then the cloud will tend to rise relative to the lines as you moved toward lower OATs.

This is where engineering judgement comes into play; if you observed such a rise, you might conclude it is not a concern if the average line through the cloud followed the reset line. You could even adjust the lines to reflect the reset schedule.

I'll provide some additional insight on how to interpret the cloud in this area in more detail in a subsequent column discussing the analysis techniques.

FIGURE 6 MOA with preheat.



MOA with Preheat (*Figure 6*)

If the outdoor air continues to drop below the inflection point identified in *Figure 5*, then the MAT will drop linearly along with it, assuming a constant MOA percentage. We can create the line by selecting an extreme OAT and using *Equation 3*.

The slope of this line is directly related to the MOA percentage. Thus, when we plot real data against it, the shape of the cloud relative to the line is an indication of how well the system is following the desired MOA. And, if we monitor the operation of the preheat process and add that data to our chart, we should not see it active until after the data cloud starts to bend.

Integrated Economizer Operation (*Figure 7*)

If the outdoor air temperature rises above the MAT setpoint, an integrated economizer will continue to use 100% outdoor air, and in a perfect world the OAT will equal the MAT over this range.

A real data cloud in this area will show scatter for many of the reasons listed previously. In particular, if the return damper blade seals are leaking, the cloud will tend to be shifted upward from the line of perfection. The shift will be larger at lower OATs than higher ones as illustrated in *Table 1*.

For a nonintegrated perfect economizer, this line does not exist. As a result, the data cloud associated with a real, nonintegrated economizer will have a gap in this area.

MOA with Cooling (*Figure 8*)

In most climates, a point comes as the OAT increases where cooling a 100% outdoor airstream will use more energy than reverting to minimum outdoor air. That creates another inflection point in the lines, and we can establish the line by picking an extreme OA condition and using *Equation 3*.

Real systems make this decision using a variety of techniques. Because the spreadsheet we are discussing uses outdoor air temperature as an axis, I base the inflection point on the fixed OA dry-bulb setpoint strategy, tailored to the specifics of the climate and application.‡‡‡ Thus, scatter in the real data cloud vs. the perfect lines in this area can be due to the nature of the changeover strategy in use relative to what the fixed OA dry-bulb strategy would do in addition to the factors mentioned previously.

Note the gap between the dark blue integrated economizer line and the green MOA line. This gap will exist unless the economizer high limit setpoint is the same as the average return air temperature.

Data from a real system should show a gap in the cloud at this point if things are working properly. If there is not a gap in the data cloud when one exists in the lines, it suggests that the high limit setpoint is different from what was used to set up the chart and that an opportunity to optimize it may exist.

Also note that systems with a nonintegrated economizer will jump from the light blue economizing line directly to an extended version of the green MOA line, i.e., the dotted extension shown in *Figure 8* . That means that if the system you are working with is supposed to have an integrated economizer and displays a gap in the data in this area, then perhaps you have found an opportunity.

But before you convert to an integrated economizer (required by most current codes), be aware that one of the reasons for using a nonintegrated economizer is to prevent compressor short-cycling and failures for systems that do not have the turndown capability needed to deal with the extremely low coil loads that will be seen at low OATs.§§§

As was the case for the preheat portion of the chart, the slope of this line is directly related to the MOA

FIGURE 7 Integrated economizer operation.

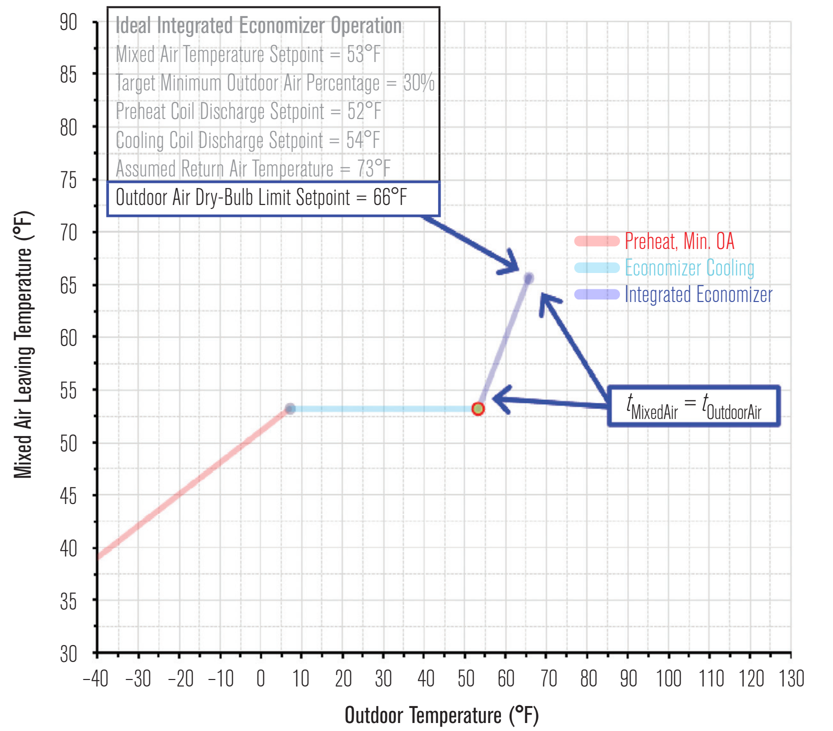


TABLE 1 Impact of return damper seal leakage on MAT.

				SYSTEM MAT SETPOINT = 56.0°F
				SYSTEM RAT = 72.0°F
OAT (°F)	PERFECT MAT (°F)	ACTUAL MAT WITH THE INDICATED RETURN DAMPER LEAKAGE RATE (°F)		
		5%	10%	15%
56.0	56.0	56.8	57.6	59.1
58.0	58.0	58.7	59.4	60.7
60.0	60.0	60.6	61.2	62.3
62.0	62.0	62.5	63.0	63.9
64.0	64.0	64.4	64.8	65.5
66.0	66.0	66.3	66.6	67.2
68.0	68.0	68.2	68.4	68.8
70.0	70.0	70.1	70.2	70.4
72.0	72.0	72.0	72.0	72.0

‡‡‡For details on how to do this, visit https://tinyurl.com/PerfectCHWLoad

§§§Nonintegrated economizers can be encountered in existing buildings and on packaged systems with limited turndown capability. Small chilled water systems can also exhibit short-cycling when serving integrated economizer loads, forcing the operators to defeat the integrated economizer to prevent compressor failures. One potential solution to this dilemma is to create a thermal flywheel, as illustrated in this blog post and the related videos: https://tinyurl.com/IntegratedEconPlusFlywheel percentage, and the shape of the cloud relative to the line is an indication of how well the system is following the desired MOA. If we add mechanical cooling operation data to our chart, we should not see it active until after the data cloud starts to bend.

MOA Percentage (*Figure 9*)

As discussed, the real data cloud should follow the slope of the lines when the system is on MOA if the system is functioning properly. The slope of the MOA lines will lie somewhere in-between the horizontal line associated with no MOA and the 100% OA line associated with the operation of the integrated economizer.

If the data cloud bends at the inflection points but does not follow the design percent MOA line, you can estimate the MOA percentage by "eyeballing" a line through center of the data cloud.

Interactions with Other Processes (*Figure 10*)

The spreadsheet as we have discussed it so far can paint a nice picture of economizer performance. You can add other lines to the chart to provide additional insights. *Figure 10* illustrates what the spreadsheet looks like with data loaded into it, along with supplementary diagnostics to highlight unnecessary preheat, cooling and reheat. I suspect some of you can already see hints of where problems lie as you compare the data cloud to the lines, just like the operating team I was working with did.

FIGURE 8 MOA with cooling.

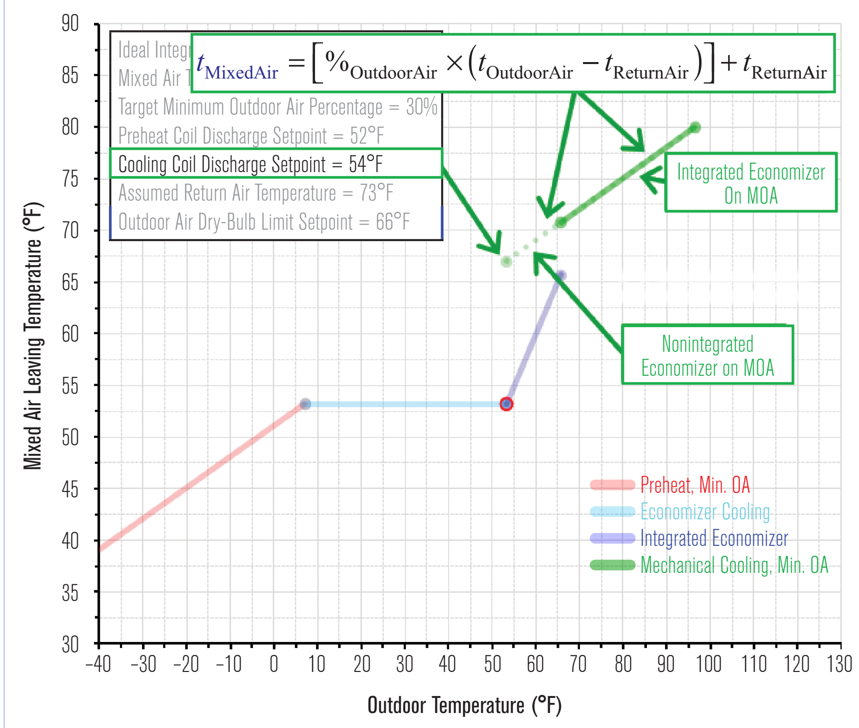
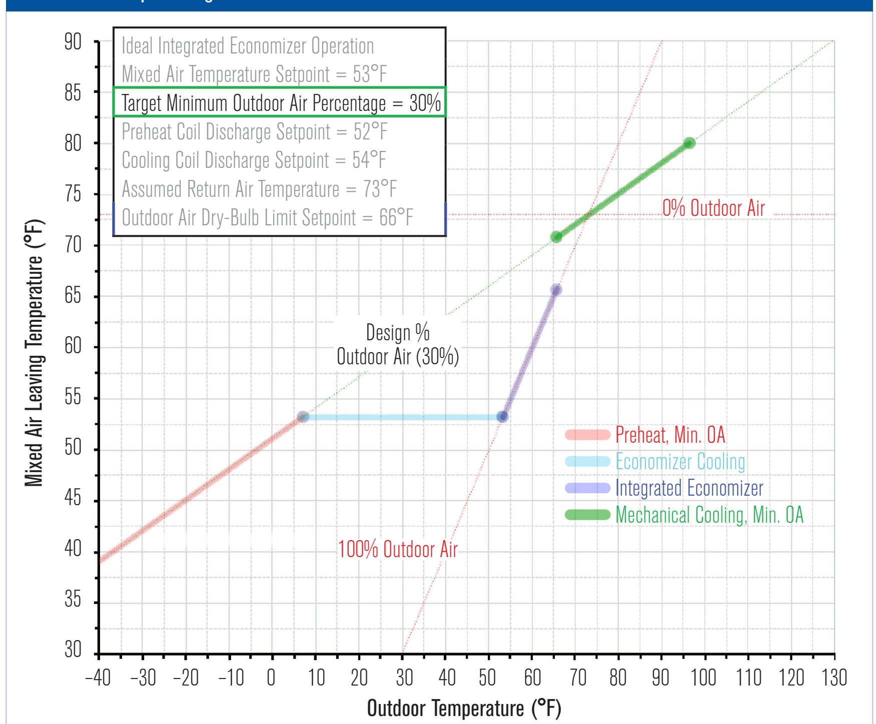
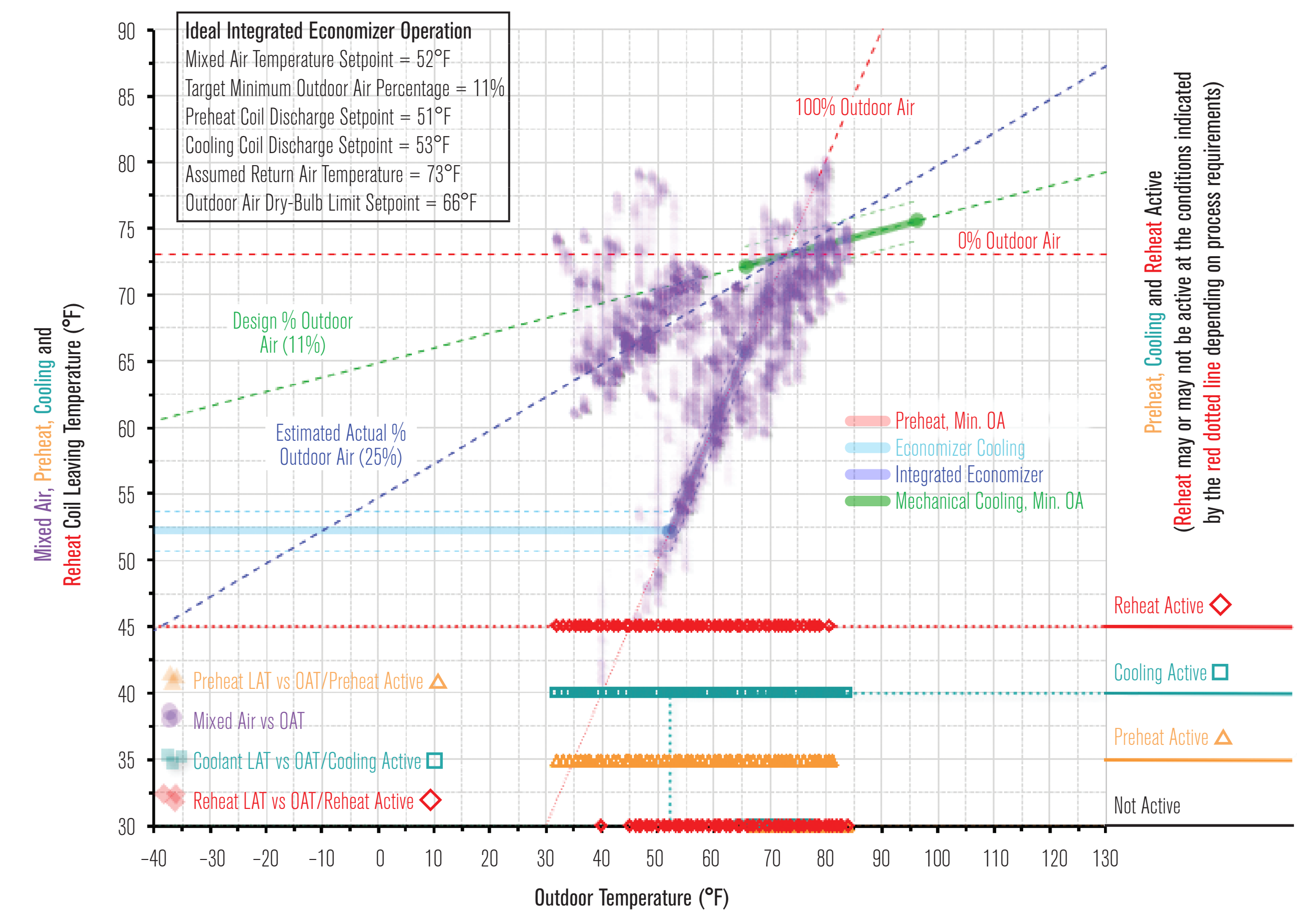


FIGURE 9 MOA percentage indication.



- Reheat could legitimately be active for this system at any time, as indicated by the red dotted line. And as you can see, reheat was active some of the time, but there may be ways to minimize that.
- Chilled water cooling should not be active until the economizer high limit setting is reached, as indicated by the dotted teal line. As you can see, there is an opportunity here since chilled water was used before necessary.

FIGURE 10 Rooftop unit data plotted against the perfect economizer lines.



- For this system, given the climate, the point when preheat would be active is off the chart. Yet preheat was active, along with chilled water cooling and reheat, so a definite opportunity for improvement.

I'll take you further down the analysis path in a future column.

Conclusion

Hopefully, in addition to illustrating technique, this column and the "Modeling Perfection" column help you see how one thing can lead to another. Deviations from perfection in the chilled water plant data cloud led the team to explore their AHUs. Applying the perfect economizer concept there revealed where the root cause of the problems lay, allowing them to focus their O&M and capital projects to maximize the benefits.

Acknowledgments

I want to thank my fellow column writers and editor for their thoughtful and insightful review comments, which helped me fine-tune the final draft of the column.

And I wanted to thank CERL and Dewberry for the latitude they granted me when I worked with them on a recent project, which gave me time to further develop some of the concepts I discuss here. ■