Trend Analysis for Commissioning

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This article shows how using automated analysis on trend data from energy management and control systems (EMCS) can serve as a powerful tool for troubleshooting control systems.

Many EMCS systems are never commissioned fully or correctly, leaving the building operator with a less than fully functioning system.\textsuperscript{1,2}

The main obstacle in providing better building performance has been the complexity of modern EMCS systems. They have evolved rapidly, requiring extensive training of designers, installers and users. Where this training is not present, many of the potential advantages of EMCS end up not being realized.

Using Trend Data

To maximize EMCS performance, the control system has to be tested and tuned initially during commissioning. Ideally, it is then maintained and tuned on a continuous basis to achieve better energy efficiency than comparable buildings. Benchmarking tools exist for such comparisons.\textsuperscript{3}

One of the most powerful tools to implement testing and tuning is the trending of control points, or recording of values over time. A control point includes any external sensor of the system, such as a room temperature sensor (physical points), and also internally calculated values (virtual points), such as temperature setpoints or control loop output.

Usually, too much data is generated by the EMCS system to manually check results by creating graphs. A visual check is useful since it reveals details about a particular piece of equipment, but setting up visual representations, and getting scaling, overlays, colors, etc., adjusted usually takes time. So, while visually checking data is illustrative, this is not a workable method for hundreds of trends and/or long time periods. Figure 1 illustrates the problem.

A typical trend, showing values over time, shows the room temperature being controlled to stay within two setpoint values (heating setpoint blue, and cooling setpoint red). The trend shows that temperature is not maintained over the prescribed range: over the course of two weeks, the temperature either exceeds the cooling setpoint (too hot) or falls below the heating setpoint (too cold) on many occasions.

This shows a good picture for one


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area. The question is, how can a building engineer or owner get an idea of performance in the entire building or plant? This might require looking through several hundred of these time trends. If complaints come and go over the course of several months, looking at a two-week sample may not provide the answer either.

How then can we make better use of the large amounts of available information?

Available Analysis Tools

A number of techniques for automatic trend analysis have been implemented in commercially available tools. These tools all cover different methods and approaches by automating part of the process required to interpret the data generated by the EMCS. Some of them offer a far-reaching level of sophistication that allows the commissioning agent or building engineer to analyze building behavior in a fraction of the time required to manually detect errors and anomalies.

In addition, commercial services are becoming available from some of the larger control manufacturers that provide off-site building analysis and reporting on a monthly basis. Similar to a service contract for HVAC equipment, this is a fully outsourced activity that is easy to implement, such as a commercial version of the virtual facilities engineer described by Rogers and Russo.

Unfortunately, the first cost involved in acquiring any of the tools or services mentioned previously may deter many operators from considering them. In this respect, access to a better understanding of readily available methods that do not require a significant investment may be helpful.

This article deals with methods and techniques we have found successful in analyzing trend data during commissioning new buildings, and troubleshooting or retrocommissioning existing facilities. These methods are not software specific and can be used to obtain better insights into building performance with minimal expenditures.

Techniques

The author does not focus on the basic methodology of using a trend to verify performance. The question, “How do I tell if the correct sequence of operations is performed by looking at a trend?” falls outside the scope of this article. Rather, we will discuss how to analyze certain trend behavior for hundreds of trends at a time.

The first problem to be aware of is that the amount of data generated after trends are set up overwhelms many standard PCs. Machines used for trend analysis should be at the high end of available products. A trend database of 6,000 points in a 150,000 ft² (14,000 m²) office building trended for a period of two weeks at one-minute intervals will result in about 120 million records. This is much more than what is usually trended during normal operations, but for commissioning or troubleshooting purposes, we routinely trend every single point in the system, and at one-minute intervals, rather than 10 or 15 minute
intervals. Depending on the file type used, this will be several hundred megabytes, and is usually too large to transmit over the Web, unless it is done in real time as values are generated.

All of this data has to be imported into the tool used for analysis (such as a spreadsheet or dedicated analysis tool) including tools for visualization in charts and graphs.

In our experience, trend visualization requires a dedicated software product that allows multiple trends to be overlaid, placed on multiple scales for comparison, is capable of showing tens of thousands of control points quickly, and allows zooming and scrolling through time series. In addition, built-in curve smoothing, regression analysis, peak finding and a number of other elementary tools are prerequisites for dealing with large amounts of data. A spreadsheet is not powerful or easy enough to use to perform most of these functions.

Trend graphing and statistics software products are available (search for “graphing and data analysis software” on a Web search engine). Most of them retail for several hundred dollars.

### Automated Analysis

We will not detail the data acquisition and import challenges further. The subject of converting data and formatting it correctly to allow transfer between platforms will be addressed in a separate article in the near future.

Instead, we will concentrate on what to do with the data once it is converted into a usable format. Usable format in this regard is any format that can be read by the graphing software and/or a spreadsheet. Comma-delimited files (CSV), ODBC-compliant databases (e.g., Microsoft® Access) and standard spreadsheet formats (XLS) are the most typical. Most graphing programs will read these.

To analyze a building’s performance, you will first want to get a bird’s-eye view of the entire data set. This will highlight areas that are likely to be problems, and you can then focus in on these. Figure 2 shows this as the first part of Step 3, statistical analysis. This statistical analysis is part of the graphing software we discussed earlier. Most packages feature statistical analysis such as number of data points, average, standard deviation, min/max, start and end time, sample interval, etc.

As a first step, this will let you cull trends from the database and allow you to find inactive trends. A simple minimum/maximum/average value will show trends that do not change over time, or that are exceptionally high or low. In addition, extreme values can indicate sensor errors (such as -409°F [-245°C] for room temperature), and the number of points in a trend can indicate that data is missing.

### Offset From Setpoint

The next step is to take the different trend series and find the worst performers. In other words, where Figure 1 showed a temperature that was not controlled well, Figure 3 shows better performance.

How do we automatically go through all trends, and sort them by performance? How do we find the trouble areas we should be focusing on?

This can be done with an offset-from-setpoint analysis. It mathematically calculates how much a trend point deviates from its setpoint(s), and for how long.

We can take all values above the setpoint and calculate the area between the actual value and the setpoint. The same is then done for values below the setpoint. The larger these two areas are, the worse the value adheres to its setpoint.

The formulas for such an analysis are:

\[
\text{Offset}_{C,n} = \max(0, \text{Temp}_n - SP_{\text{cooling},n}) \quad \text{for cooling} \tag{1}
\]

\[
\text{Offset}_{H,n} = \max(0, SP_{\text{heating},n} - \text{Temp}_n) \quad \text{for heating} \tag{2}
\]

\[
\text{Time}\_\text{step}_{n} = \text{Time}_n - \text{Time}_{n-1} \quad \text{for both} \tag{3}
\]
Offset\_C = -\sum_{n=1}^{N} Offset_{C,n} \times Time\_step\_n \text{ for cooling} \quad (4)

Offset\_H = -\sum_{n=1}^{N} Offset_{H,n} \times Time\_step\_n \text{ for heating} \quad (5)

Where Offset\_C,n is the difference between the actual value Temp\_n and the cooling setpoint SP\_cooling,n at trend Point n. By taking the maximum of 0 and the difference, all negative values are ignored. These negative values are discarded because they indicate that the actual trend value is not above the cooling setpoint, and, thus, do not indicate a problem in control. Similar logic applies for the heating offset.

Time\_step is simply the time difference between one trend point and the next. In most cases, this is a fixed interval, for example five minutes, and is determined by the initial trend setup at the EMCS. However, in many cases trend data may be “dropped” or lost, so that actual trend data may not occur in regular intervals. The trending interval also may be changed at the EMCS during the trended period. For this reason, Time\_step should be calculated for every trend point.

By multiplying Offset\_n and Time\_step\_n for all trend points and summing up all of the resulting values, the area between setpoint and temperature outside of setpoint is calculated.

The last step is to divide the resulting area by the total time of the trend interval over which calculation takes place, so that trends measured over different time intervals can be compared. In this way, the result for a point trended and calculated over three weeks will not be larger than the result of a point trended and calculated over one week, provided their control performance is similar.

\[
Offset\_C,\text{norm} = \frac{Offset\_C}{Time_N - Time_1} \quad (6)
\]

Where Time\_N is the timestamp of the last trend point, and Time\_1 is the time stamp of the first trend point. Each of the Formulas 1 – 6 can be easily implemented in a spreadsheet or a graphing package. The result for each trend are two numbers, one offset for how badly overheated and one offset for how undercooled an HVAC zone was during the trend period. This offset takes into account both the amount of time the zone was outside of setpoint values, and the magnitude of this deviation.

By copying the minimum and maximum trend values next to the offset for cooling and heating, a clear picture emerges about how well every zone performed.

When looking at, say, 200 VAV zones, this method produces a table with numbers for each zone, and this table can be sorted by the offset size. The 10 worst offenders now can be easily picked out and studied more closely by visualizing the trend data in a graph and studying it in more detail.

Instead of making a table, the resulting offset numbers also can be mapped out onto a floor plan by putting the results cells into the approximate location of a zone on a spreadsheet. Simple line draw tools within the spreadsheet serve to provide a primitive rendition of the building outline, and the spreadsheet automatic formatting function shows large offset numbers in yellow and very large offsets in red.

In this way, an immediate idea is obtained of problem areas within the building. This might show problems in a particular exposure (west in Figure 5), problems clustered within the vicinity of a main supply duct, etc.

Once the spreadsheet is set up, the analysis can be repeated...
through the described procedure by hand and knowing at the end of this exercise where all the trouble spots are in a building. No more arguments such as “it’s OK now, but last week it was always hot” will muddy the picture. The analysis shows overall performance over the entire trend period.

A sample spreadsheet with these formulas can be downloaded from the Web.9

This analysis can be further refined by looking only at values during occupied hours, or when the supply fan is running. Special emphasis can be given to values far in excess of setpoint by raising the value to a power, so that the overall integral becomes higher (Figure 6). This modifies the formulas given earlier to:

\[
\text{Offset}_{C,n} = \max \left[0, (\text{Temp}_n - \text{SP}_{\text{cooling},n})^{\text{exp}}\right] \quad (7)
\]

\[
\text{Offset}_{H,n} = \max \left[0, (\text{SP}_{\text{heating},n} - \text{Temp}_n)^{\text{exp}}\right] \quad (8)
\]

Where the exponent exp provides weighting of the result. For example, if close control of an area is required (e.g., a cleanroom), then exceeding the setpoint by more than a degree even briefly may be a bigger problem than exceeding the setpoint by a tenth of a degree for a long time. Increasing the number exp will highlight this and produce a larger offset number.

The earlier examples were all based on maintaining room temperature. However, the same analysis can be used for any other point. Most control points are maintained at a single setpoint, rather than the dual setpoint (or setpoint + deadband) method used for thermostats. For example, a variable speed pump may be driven by maintaining pressure in the hydronic system at setpoint. The pressure setpoint is a single trend point. A variable air volume terminal will be controlled to provide airflow to match a cfm setpoint. The cfm setpoint will be a single trend point.

The same method outlined earlier can be used to determine a single setpoint analysis (e.g., to see which VAV terminal on a floor is often short of air). Instead of using two different setpoint variables \( SP_{\text{cooling}} \) and \( SP_{\text{heating}} \), only one variable is used, such as \( SP_{\text{cfm}} \). This is substituted in Formulas 1 and 2, and \( \text{Offset}_{C} \) and \( \text{Offset}_{H} \) for cooling and heating, respectively become offsets above and below setpoint for general use. Another typical example for this method would be to look at how well each VAV zone is maintaining discharge temperature.

**Baseline Comparison**

Another method of analysis is baseline comparison.10 By anticipating how equipment should operate, actual trends can be compared to expected trends. The mathematics of comparison are similar to offset from set point analysis. Instead of using a setpoint trend for comparison with an actual value, a calculated baseline trend is used.

Baselines can be applied to all kinds of trends when a setpoint comparison will not give an immediate answer. For example, an air handler with sufficient cooling coil capacity may be maintaining discharge air temperature at setpoint even though the economizer is malfunctioning, and wasting energy. Thus, performing an offset-from-setpoint analysis will not show any problems.

The temperature relationships between return air, outside air, mixing air and supply air are well understood in an economizer.11 This relation thus can be modeled as a baseline for comparison with actual sensor data. Even if the air handler maintains setpoint, faults can be shown by using a baseline analysis. The article by David Sellers11 shows how to do this graphically. Alternatively, the analysis also can be done automatically with the offset-from-setpoint analysis math by creating a baseline and substituting it for the setpoint in the equations where

- \( OAT \) is the outside air temperature,
- \( MAT \) is the mixed air temperature,
- \( RAT \) is the return air temperature,
- \( SP_{\text{MAT}} \) is the supply air temperature setpoint.
BSL is the baseline for comparison to mixed air temperature. It is not a setpoint, but instead is calculated from other temperatures to show how mixed air temperature should behave in a system that works correctly.

If \( SP_{SAT} < OAT < RAT \), the economizer should be 100% open, and \( MAT \) should equal \( OAT \), so \( BSL = OAT \) \hspace{1cm} (9)

If \( SP_{SAT} > OAT \), the economizer should modulate to maintain \( SAT \) at \( SP_{SAT} \), and \( MAT \) should equal \( SP_{SAT} \), so \( BSL = SP_{SAT} \) \hspace{1cm} (10)

If \( SAT > RAT \), the economizer should be at minimum position; let's say this means introducing 15% outside air, then \( BSL = 15\% \times OAT + 85\% \times RAT \) because that's what \( MAT \) should be. \hspace{1cm} (11)

For each point in time of an air handler trend collection, Formulas 9 – 11 can be used to calculate the baseline for mixed air temperature. This baseline is then used as a virtual setpoint for comparison against mixed air temperature. The offset-from-setpoint analysis is run (and now becomes an offset-from-baseline). If large offsets result, the economizer is not working correctly.

Note that, in the previous formulas, the baseline may have to be corrected for fan heat. As mixed air becomes supply air, its temperature may rise by a few degrees depending on the installed fan motor. Since the fan motor heat may vary in a VAV system, an average value may be inserted (say 2°F [1°C]) after evaluating a few actual values. See the substitute for Formula 10, where \( FH \) is fan heat gain in degrees Fahrenheit (other formulas remain the same):

\[
\text{If } SP_{SAT} > OAT, \quad BSL = SP_{SAT} \times FH \quad \text{(12)}
\]

At the end of the analysis, the offset number will give a time-averaged result of how much the mixed air temperature deviated from expectations. If this offset above baseline is on the order of 5°F – 10°F (3°C – 6°C) or more, then clearly the economizer is stuck open, and mixed air temperature regularly is above expectations.

Many ways of modeling baselines exist, from using actually measured data of correctly running equipment, to mathematical modeling (as done in the previous example), to neural network analysis.\(^{12}\)

**Lead/Lag Operation**

Lead/lag operations also can be easily analyzed. The sum of two status or start/stop trends must equal 1 in a typical duplex setup. Similarly, if a supply fan’s operation automatically triggers an exhaust fan’s, then the sum of status or start/stop trends must be either 0 or 2, but never 1. Note that a certain time delay may exist, so that care must be taken not to generate errors if a one-minute delay exists between supply fan and exhaust fan start, and one-minute trends show supply fan on but exhaust fan off right at that moment.

The following example shows this: dual fan coil units are serving a space, together with an exhaust fan. The sequence calls for either Supply Fan 1 or Supply Fan 2 to run (but not both). If either supply fan is running, the exhaust fan (EF) should also run. We can numerically add the fan start-stop (SS) commands as follows:

\[
\text{Baseline} = SF1.SS + SF2.SS \times 2 + EF.SS \times 4 \quad \text{(13)}
\]

This means that baseline values above 6 or below 5 should not occur during normal operation. The gray areas in the Figure 7 show where errors occur. By taking a minimum and maximum of all baseline values, we can immediately see if the fans operated incorrectly at any time. By taking a maximum setpoint of 6 and a minimum setpoint of 5, we also can run an offset-from-baseline analysis and get an idea of how often errors occur, or whether we are looking at very incidental user-overrides.

**Stability**

Stability can be assessed by counting local minimum and maximum trend values, or a count of peaks. If the number of peaks is too high within a certain time, the equipment under examination is cycling. This method also is available in spreadsheet format from the Web.\(^{13}\) Some trend analysis programs have this feature built-in already.

**Other Types of Analysis**

Some of the other analysis methods are more complex, although many can still be done by spreadsheet formulas or database macros. Some of the commercial tools mentioned previously contain more than 50 of these analysis methods preprogrammed:
• **Sensor calibration.** Sensor behavior can be predicted to some degree. For instance, for a VAV reheat system, air terminal supply temperature should equal air handler supply temperature when the terminal heating valve is closed. Some temperature rise may occur in the duct despite duct insulation. However, if a difference in sensor readings rises over the course of a year, it indicates sensor drift, and the system can be made to automatically alarm.

• **Fighting coils or fans.** Several air handlers serving the same space may work against one another. A typical example would be air handler fan speed controlled by building pressure; as one unit speeds up, another slows down, resulting in constant cycling. While this keeps building pressure constant, it does not meet the designer’s intent. Another example would be computer room air-conditioning (CRAC) units. Half of these may be humidifying a common space, while the other half dehumidifies at the same time, costing valuable energy. Mathematical analysis would include a rule that alarms when one unit slows down simultaneously to another speeding up repeatedly or an alarm whenever more than one CRAC humidifier and one CRAC reheat coil are active at the same time.

• **Starved systems.** If the airflow from a VAV terminal does not rise while the cfm setpoint rises, or if the airflow varies below setpoint while the damper remains fully open, the box does not receive enough air, indicating damaged/constricted ductwork or design flaws. Note that the methods listed above all require some “intelligence” or building modeling to be incorporated. Before analysis can be done, the trend samples have to be assigned a certain role within the HVAC system: is a trend a setpoint or a room temperature or a status signal? These assignments of trend function have to be done by manual intervention, so that fully automatic analysis systems are not possible. However, some systems can be set up by assigning correct roles to each trend just once. From then on, data is collected and analyzed automatically.

**Conclusion**

The field of building commissioning is rapidly evolving. LEED® accreditation has played a role in raising awareness about the importance of getting buildings to function as intended. Rising energy prices are continuing to make energy efficiency a more important factor in overall building cost.

Building automation systems often are commissioned inadequately. Commercial tools are becoming available to help in the process of automating fault-finding and building performance evaluation.

However, training for engineers, commissioning agents and building operators remains an important factor in achieving good building energy efficiency, since some human intervention will always be required.

In this article, we shared some of our techniques and experiences in commissioning buildings and referred to some of the developments in this growing field to provide a basis for discussion and an incentive to bring forward ideas.

**References**


