

## **Control Sequence of Operation – Getting it right from OPR to Systems Manual**

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### **Synopsis**

Perhaps one of the most challenging elements of any project involving DDC Controls is developing and implementing a Sequence of Operation for the major building systems. Possibly because of a lack of formal HVAC controls education in college, perhaps because of the proprietary nature – even in the age of open protocols - that has surrounded DDC controls, most of us involved in either the design or operation seem to regard the control system as a “black box.” This lack of knowledge and understanding often leads to a disconnect between the design concept (how it should work) and the end result (how does it actually work); the project suffers for it. This paper will point out the importance of developing an early version of the sequence of operations (SOP) in the design phase and the value of continuing to refer back to it throughout the construction process.

### ***About the Author***

Bernard Keister is a senior commissioning and controls engineer for Guttman & Blaevoet Consulting Engineers. Prior to moving into consulting, he worked for 15 years in the field as a control systems contractor to design, install, and train building owners on the optimal use of their Building Automation Systems. He has a BS in Mechanical Engineering from Cleveland State University and is a registered Professional Engineer in the State of Ohio.

## In the beginning...

If we distill the concept of the sequence of operation (SOP) into its most rudimentary form – it's clear to see that the idea of “how should this work” when the project is done is actually present from early in the design process. During the programming phase and/or development of the owner's project requirements (OPR) document in the case of a LEED® project, information is collected that directly affects the final SOP on a project.

### **OPR Development**

The OPR is written documentation of all the functional requirements of the facility and the expectation of how it will be used and operated. It is meant to contain information on occupancy, use of the facility, energy performance, environmental performance, thermal comfort, indoor air quality, and quality of materials and equipment. While many of the questions that are answered in the development of the OPR do not generate items that pertain to the building SOP (Do we want to look for bamboo products for the architectural accents?), some of the questions actually do:

- What are the expected hours of operation of the facility, in a general sense?
- What are the knowledge level and/or expertise of those who will be interacting with the system? Is the primary building operator a store manager, janitor, or a trained maintenance person with HVAC repair knowledge?
- Will the tenants/users of the building have any interaction with the control system via after-hours overrides, local adjustment of space temperature set points, or lighting controls?
- Are there critical environmental requirements – museum exhibit, healthcare, laboratory, clean room?
- Does the Owner require emergency and/or redundant operation of Electrical/HVAC systems?

The evaluation of questions like these begins to suggest certain elements that should be recorded into a design narrative that speaks to desired operation of the building. It is not necessary at this point to have the fully developed SOP that is issued in the contract documents, but rather a record of “concepts” that will be more fully detailed in the later phase of the project. Following on order from above – here are some suggested concepts that could be recorded:

- Some, but not all of the space will be unoccupied overnight – consider flexibility in ventilation, and mechanical cooling capacity. Define modes of operation for the different uses of the zones.
- If the building operators are not as knowledgeable, consider most of the control adjustments should be automatic – the operators can have some fundamental adjustment of set points, but they should be limited to a range that will not cause the system to operate inefficiently or improperly. If, however the staff is more sophisticated, allow for some manual override modes that can be implemented for special operating conditions

(i.e. routine maintenance, summer session floor waxing in a school) – with indication that the system is not necessarily in full automatic mode and may not be performing to optimal efficiency.

- Consider if the space is leased – will the owner want to bill for after-hours HVAC and lighting? If the users can adjust space conditions locally, how much latitude (+/- degrees) will they be given?
- Though specific space condition requirements lead us into basis of design (BOD) and hardware specification realms, it can also dictate what modes of operation may or may not be used on a given mechanical system. For example, a museum space will not use a night purge for pre-cooling an exhibit space as this would bring in unnecessary amounts of cool, humid air.
- Failsafe or fall-back operation will dictate additional complexity as the building systems adjust to the new priorities in space conditioning.

## ***Basis of Design***

As the design professionals begin to flesh out the method of execution of the HVAC, electrical and plumbing design, additional details begin to surface for inclusion into the SOP. By definition, the BOD is a narrative of what the design professional has developed to respond to and meet the owner's project requirements. The BOD will be qualified with assumptions and criteria used.

## **Example**

- OPR: The owner wishes to use district chilled water for cooling purposes, as the cost is lower than on-site generation. They do have some critical cooling needs, though, and would like some type of back-up if the district water fails.
- BOD: The engineer suggests that a primary/secondary system be installed, with a modulating valve on the chilled water return to the district. The return water to the district will be monitored to maintain a 10 degree F temperature difference from the supply. Under low load conditions, the primary return water valve will modulate to bypass the water back into the secondary system (circulated by secondary CHW pumps), maintaining the 10 degree differential. The district supply will be monitored for flow and for high temperature. If there is a loss of flow and/or the supply temperature rises too high, the building system will isolate from the district water and energize the on-site mechanical cooling in series in the secondary system. The building automation system (BAS) will disable all non-critical cooling loads by closing their cooling valves, as the on-site capacity is only designed for the loads of critical areas. The BAS will automatically check for the return of district chilled water by opening the isolation valve for five minutes every hour to 5% of full flow to see if temperature or flow conditions can be met.

We can see from these two bullet points the increase in detail as the project moves through the programming phase. We haven't gotten into the specifics of how the secondary system will be

working exactly, nor have we finalized the back-up chiller yet, but we can see how recording this level of detail is building the fundamentals of the SOP.

## **Construction Documents – Typical Problems**

As the project design moves closer to final bid documents, it becomes important that we present detailed documentation about how we want the equipment to be controlled. Traditionally, controls design has been presented in three separate ways, via control diagrams, points lists, and the sequence of operation. Unfortunately, for many reasons, including lack of time, fee, and experience, the complete diagrams and points lists don't always make it into the final bid set, and it becomes even more critical that the SOP is clear, detailed, and useful.

### **Lack of Detail**

The usual problem with the SOP in the bid set is that it is not sufficient for use by the controls contractor for bidding and installation. If the narrative was generated in the OPR or BOD documents, perhaps the detail was not filled in enough to answer all the contractor's questions.

Example: AHU-1-1 will run during occupied hours. The gas heat and mechanical cooling will be modulated as necessary to maintain the space temperature set points.

Questions: What are the occupied hours? What will the unit do outside of those hours? How does the unit transition from occupied to unoccupied and back? The mechanical unit schedule notes that the unit comes with an airside economizer – how should this be controlled?

### **More Detail – but Gaps**

Alternatively, perhaps the designer is using a boiler-plate sequence generation method; choosing from pre-written sequences that cover most applications or offer a menu of options that the designer must selectively delete to arrive at the project-specific SOP. Unfortunately, if the designer is rushed, or perhaps is not knowledgeable about control strategies, truly un-executable SOPs can go out with the bid documents.

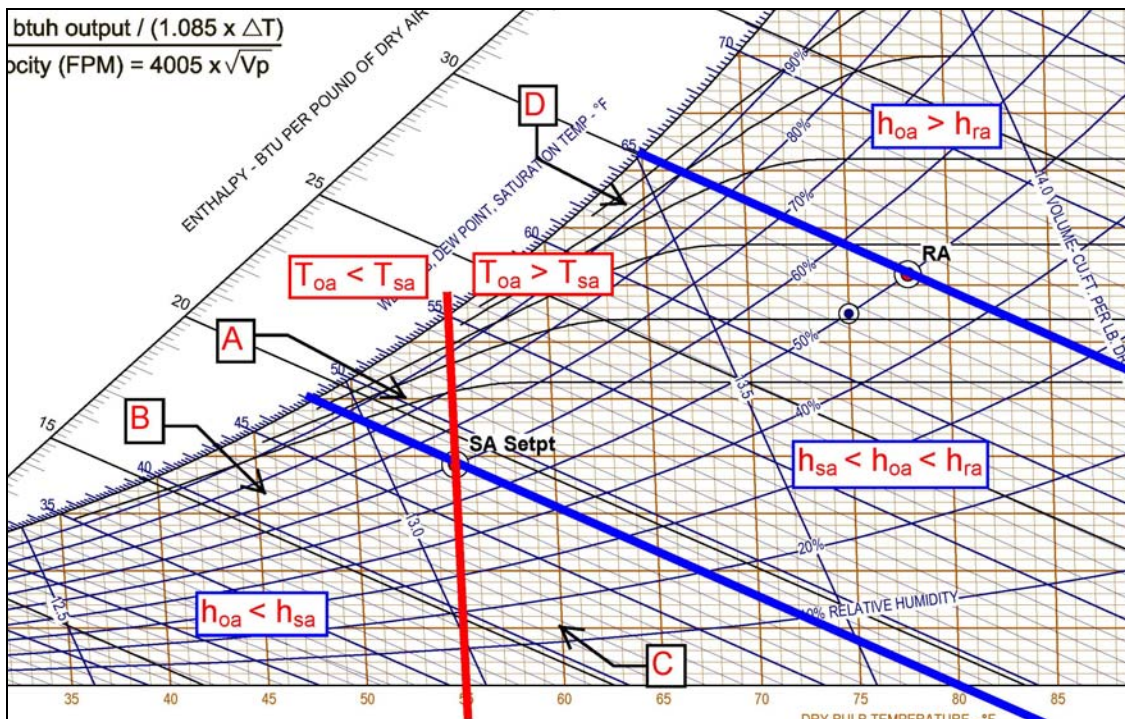
Example: I caught this sequence that had been sent out from a “pick-and-choose” master spec: (Figure 1 - The bold letters were not in the original sequence). To illustrate the difficulty of the SOP as written, I decided to lay out on a psychometric chart (Figure 2) for the design engineer just what their sequence would be asking the controls contractor to accomplish – see Figure 2 and the bold letters in the SOP. You'll notice Area “C” is not accounted for and Area “A” is covered by condition 2 and condition 3, so the programmer is left to decide which has priority.

This is a great example of using a “what if” mindset when evaluating SOPs – thinking like a programmer. Expressed in other terms, for every positive expression of the control action in a certain mode, there should be an expression for the action when not in this mode. Otherwise, there can be gaps that will be filled by the contractor that might not match the designer's intent.

**Figure 1: Economizer Sequence as Issued**

1. The economizer shall be enabled whenever:
  - a. The outside air enthalpy is less than the return air enthalpy, **(A,B,C,D)** measured downstream of the return fan.
  - b. AND the fan status is on.
2. When the outdoor air enthalpy is greater than the supply air enthalpy set point, **(A & D)** the outdoor air damper(s) shall be set for 100% outdoor air
3. When the outdoor air temperature is less than the supply air temperature set point **(A & B)** the outdoor air damper, exhaust air damper, and return air damper will modulate, as appropriate, between the adjustable minimum position and full open to maintain the discharge air temperature that will meet the room thermostat demand.
4. When the return air enthalpy is less than the outside air enthalpy the exhaust air damper, return air damper, outside air damper shall be positioned to the minimum outside air position. **(Above & Right of D)**

**Figure 2: Sequence Plotted on Psych Chart**



To fill in the gaps, here is a suggested sequence with the changes underlined (Figure 3). Note that by judicious use of AND and OR, we managed to both cover the gaps and eliminate the overlap.

### Figure 3: Suggested Economizer Sequence

1. The economizer shall be enabled whenever:
  - a. The outside air enthalpy is less than the return air enthalpy, **(A,B,C,D)** measured downstream of the return fan.
  - b. AND the fan status is on.
2. When the outdoor air enthalpy is greater than the supply air enthalpy set point, AND the outside air temperature is greater than the supply air temperature set point (D), the outdoor air damper(s) shall be set for 100% outdoor air.
3. When the outdoor air temperature is less than the supply air temperature set point OR the outdoor air enthalpy is less than the supply air enthalpy set point (A,B & C) the outdoor air damper, exhaust air damper, and return air damper will modulate, as appropriate, between the adjustable minimum position and full open to maintain the discharge air temperature that will meet the room thermostat demand.
4. When the return air enthalpy is less than the outside air enthalpy the exhaust air damper, return air damper, outside air damper shall be positioned to the minimum outside air position. **(Above & Right of D)**

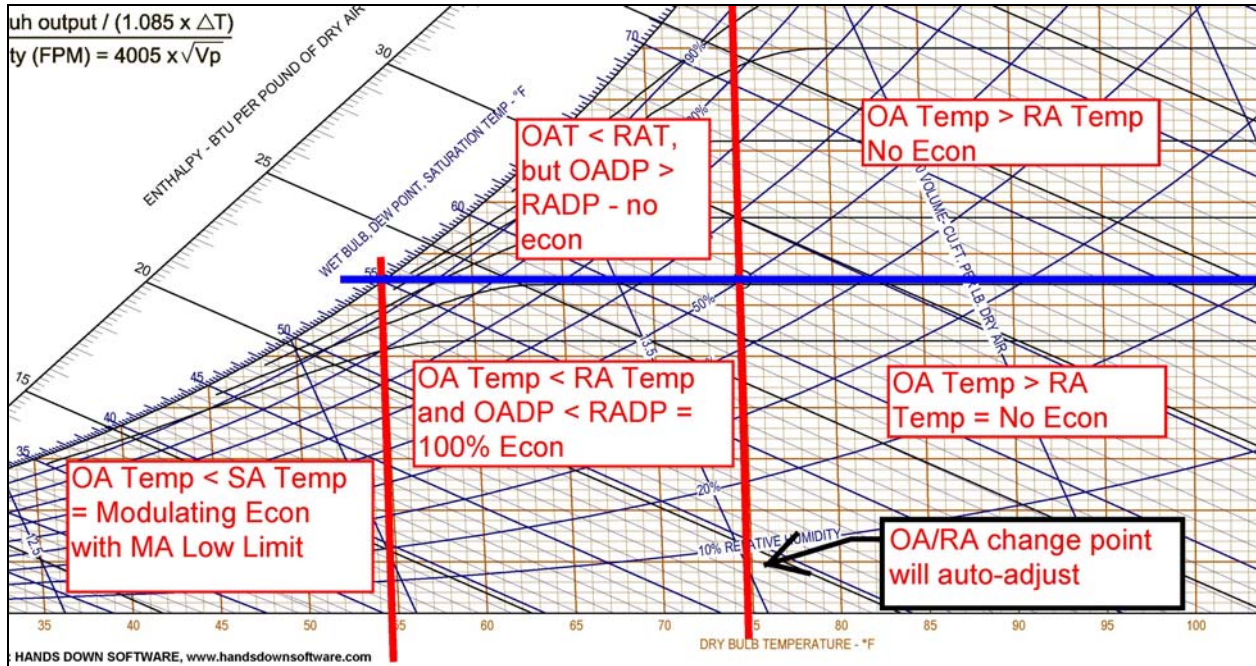
On this particular project, the investigation into the economizer sequence prompted some further discussion with the owner about their space condition requirements. It turned out that the space had humidity requirements, and that the sequence as amended would potentially add moisture to the space unless the outdoor dew point was compared to the return dew point. In the interest of being thorough, please see figures 4 and 5 for the final sequence and accompanying psych chart.

### Figure 4: Final Sequence

1. The economizer shall be enabled whenever:
  - a. The outside air dry-bulb temperature is less than the return air dry-bulb temperature
  - b. AND the fan status is on.
2. When the outside air dew point is less than the return air dew point by an adjustable dead band (3 °F), the outdoor air damper(s) shall be set for 100% outdoor air
3. When the outdoor air temperature is less than the supply air temperature set point the outdoor air damper, exhaust air damper, and return air damper will modulate, as appropriate, between the adjustable minimum position and full open to maintain the discharge air temperature that will meet the room thermostat demand.
4. When the return air dew point is greater than the outdoor air dew point OR the outdoor air temperature is greater than the return air temperature the exhaust air damper, return air damper and outside air damper shall be positioned to the minimum outside air position.
5. The economizer shall close to 0% (outside air and exhaust dampers shall be closed and return air damper shall be open) whenever:
  - a. Supply fan or return fan is off
  - b. OR mixed air temperature is less than 40 °F (1).
  - c. OR on loss of fan status.
  - d. OR the discharge air temperature sensor has failed
  - e. OR the AHU is in the morning warm-up or cool-down mode
6. The outdoor air damper shall be set to its adjustable minimum position if the economizer function is disabled. Maintain minimum outside air by modulating the outside air damper to maintain a pre-measured static pressure differential, measured immediately at the discharge of outside air damper, and with reference to outdoors.
7. Alarms shall be provided as follows:

- a. High Mixed Air Temp: If the mixed air temperature is 5°F greater than set point.
- b. Low Mixed Air Temp: If the mixed air temperature is 5°F less than set point.
- c. High or low supply air temperature.

**Figure 5; Final Psych Chart with Dewpoint Control**

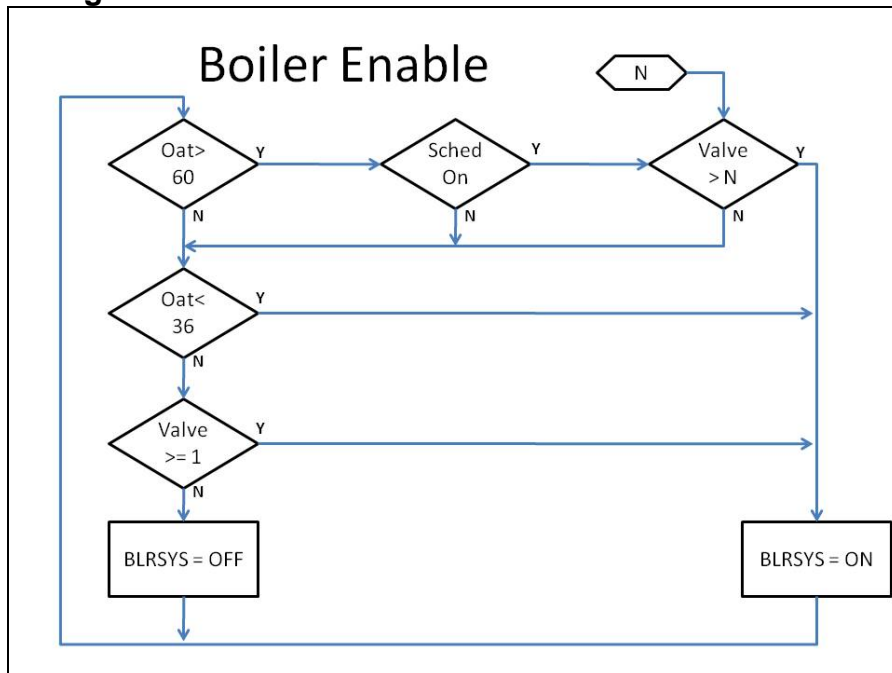


### Sequence Presentation

In the construction documents, the most usual method of SOP presentation is by numbered text list or outline as shown previously. If done with the proper use of conditionals (if...then) and conjunctions (and/or/not...etc.), this can be very effective because it breaks down the sequence into small chunks. The risk comes in the editing of sequence templates to customize them for each individual project. Close reading by the designer is required to ensure that the intended sequence actually ends up in print.

An alternative would be to use the method used by many control software makers to simplify their programming: graphical representation (see Fig 5). Similar to the flowcharting for programming or other process analysis, the designer represents the controls operation by input parameters, operation blocks and decision trees, and output or control actions. The advantages are certainly clarity and instant visual feedback for errors. The disadvantage is that the graphical sequence can be hard to generate and hard to modify for subsequent projects.

Figure 5: Flow Chart



### ***Interaction and integration with other contract documents***

The typical HVAC control documents package consists of the control specifications (including the SOP), control schematic diagrams, and the points list. Each has a different function that uniquely contributes to the communication of the control design intent to the contractor:

- Controls Schematics: **Where** – they tell us how the control components relate physically to other controls and the equipment in the system.
- Points List/Control Specs: **What** – detailed information about the “points” of information contained in the control system, input, output, hardware, software, analog or binary, and more. The specs will have even more detailed performance requirements of the control panels and other components as well as the contractual responsibilities of the controls contractor.
- Sequence: **How** – explains the actions, reactions, cause and effect of the sensors and devices. Details modes of operation and their interactions and priorities.

The SOP alone cannot fully define the control scope on a project, just as the other types of documents cannot stand alone. If you can get a competent SOP together, it can fill in gaps in the other two – if the controls contractor carefully reads the text and fills in points based upon the intended functionality implied by the SOP. Unfortunately, the SOP is usually the weakest element because it requires the most effort and diligence to get right.

## **“High-performance” versus “industry standard” and what this means for the job site**

Recent innovations in control strategies are driven by a push for more efficient building operations. These so-called “high performance” buildings, by their very nature, present unique challenges to the construction process. First, the sequences might suffer from some of the issues above; the controls contractors might not understand the new concepts. Second, control and equipment manufacturers have responded to the call from the field to provide some built-in control capabilities “out of the box” to save time in the field. Unfortunately, these efforts have been developed around an industry standard control sequence that might not be applicable. Third, non-standard sequences mean that non-standard programming will be required. Contractors are always looking for time-saving measures – if they’ve developed a library of usual control sequences to accomplish the engineer’s goals, more than likely they will try to submit and install these sequences rather than start from scratch.

Here is where the specifying engineer has to be vigilant and competent to recognize that the controls contractor might be trying to “boiler plate” their programming. The problem comes in when playing the submittal game. Step one, the contractor submits their usual sequence. Step two, the submittal is rejected by the design engineer for not conforming to the specified sequence. Step three, the controls are re-submitted with the sequence copied word-for-word from the specifications. But is this really how the controls will be installed? There is only one sure way to make sure before the project is installed and it’s too late and/or too costly to get the project back on track:

### **Controls Integration Meetings – Make the time**

Maybe not so necessary on a packaged rooftop office/warehouse space, but especially important on a complex or unusual controls project – the control integration meeting is a face-to-face involving the design engineer, the project manager and/or programmer from the controls contractor, the Cx agent at a minimum. Other attendees might be the owner’s facility personnel if this is an existing campus or facility, and the mechanical contractor.

The purpose of the controls integration meeting is to review the intended programming and controls installation against the designers’ sequence of operation and the BOD/OPR to have absolute clarity *before* too much effort and cost is expended in the field. The contractor should be prepared to share some preliminary programming or flow charts/decision trees – however they lay out the controls for their particular hardware/software. If the designer’s sequence is not understood, this is the time for the contractor to ask questions. If the contractor is echoing the designer’s sequence while thinking of inserting some boiler-plate programming, this should quickly become apparent. The time to resolve these issues is before the functional testing, and certainly before occupancy.

## ***Functional Testing – the last Bulwark***

One of the greatest arguments for having commissioning included on a project is the value that functional performance testing can add if there has been a breakdown in SOP communication and/or implementation somewhere along the construction process. In the last few months or weeks of a project, there is great pressure to place schedule as the highest priority on a job. If the project deadline is July 1, and A/C comes on beginning of June so that the paint dries, the carpet adhesive smell is being flushed, and the furniture movers are somewhat comfortable, who will pick up the detail that the VAV boxes are being balanced without the static pressure reset programming complete? All of the doors are wide open with contractors running in and out. The grand opening party with the CEO goes off without a hitch – but what happens the first time that it gets below freezing in November, and we can't get the lobby temperature above 55 degrees? The design team has moved on – the contractors are on another project, perhaps in another state.

The third-party Cx agent, conducting rigorous functional tests of all expected modes of operation to prove out the SOP can facilitate a building shakeout *while all the people with the most knowledge about the building at that point are still actively involved in the project*. Unlike most other manufactured objects, each building is unique. Even if the building is a franchise fast-food restaurant, each site has its own geographical and weather differences. Auto technicians can go to classes to gain the knowledge to be able repair one of the millions of identical cars on the road, but because of the uniqueness of a construction project it is almost impossible to recapture the knowledge level on-site after project completion without considerable time and expense.

## ***The importance of operator training – why understanding is critical***

Through the course of the project, much thought and planning is put into the details of how the building should work. We could call it an investment of intellectual capital – from the designers and perhaps the original owner's facility representative, to the control contractors and programmers. This capital is captured firstly in the OPR and BOD documents, then via the sequence published in the construction documents, and finally in how the controls contractor executes the sequence via hardware and software code, ultimately presenting it through the operator interface for use by the building operator. It would be a shame if all of this great knowledge was lost somehow and not passed on from the design/construction phase to the operations phase.

The responsibility of capturing the knowledge falls under the direction of the commissioning agent, and it can be passed on by two methods: 1) the printed operations and maintenance documents in as-built form and 2) by operations training of the owner's personnel. Of course, all the fancy sequences and programming in the world to create a highly efficient HVAC system mean nothing if at the first occupant complaint the operators override the set points and energy-efficient measures with manual operation because they don't understand how the system works. Numerous new building owners cite lack of training as a complaint, and because of this, LEED commissioning stresses the value of having a training plan and verification in place.

Some tips to improve operator training are:

- Have multiple shorter sessions spaced apart in time. Complex systems and inexperienced staffs require more time for absorption of new information. No one is served well by the all-day marathon – the students won't retain it.
- Consider multiple tracks of education for larger staffs: Basic operations for janitors, security, etc, and an advanced class for the more adept.
- Make it as hands-on as possible – the instructor should not be using the interface, have the operators use the mouse & keyboard, adjust set points and answer alarms, etc.
- Create some “what-ifs” for the operators, and then coach them as they learn to use the control system adjust set points, schedules, and modes of operation.
- Don't just sit in front of the screen – walk to the mechanical room & “fail” a pump. Watch what happens in the mechanical room. Go back to the OWS and evaluate: the system is calling for the pump, but it has no status. Verify the alarm and acknowledge or silence it. Do some troubleshooting if possible from the OWS. If not, note the number of the pump, walk to the mechanical room and “fix” the pump. Note any automatic resets of equipment. Back at the OWS, perform any software resets and log the incident. Watch for return to normal operation.

The emphasis for the operations staff should be that a building automation system is a tool, just like any of their other tools, and that it requires some training to use, so they shouldn't expect instant mastery. It is also important to emphasize that if they don't use the tool regularly, they will not become skilled in using it. In fact, it might become an obstacle or a hindrance to keeping the building operating at peak efficiency.

### ***The Importance of the Control System Man-Machine Interface***

We only have to look at the transformation of the personal computer over the last two decades to see the parallel transformation in the operator interface for today's building automation systems. Does anyone remember DOS and monochrome CRTs? They were still being installed in 1995. Obviously, using graphical interfaces to present the complex building systems, scaled floor plans and schematics with real-time system data has made full-building controls that much more operator friendly.

To ensure the best possible outcome, the specification should require the contractor to submit graphic screens for review as soon as possible (or sample screens) so that the owner may have the opportunity to get the graphical presentation that best suits their needs. The contractor should be encouraged to get some “buy-in” from the owner as they are in the process of generating and installing graphics – better to catch something before the field work is done.

### ***The potential need to re-publish sequences: i.e. the difference between the “technical manual” and the “operators’ manual”***

When you got your last automobile, you probably were made aware that there was an operator's manual in the glove compartment. Unless you are an automotive engineer, or perhaps work on cars for a living or as a hobby – the Operator's manual contains more than enough technical

support for most drivers. Now in the course of the design, and manufacture of the car, many more complex documents are generated and these can be obtained by authorized service technicians as the “technical manual.”

When we as the technical design and construction team turn over the O&M manual, as-builts, start-up sheets, functional performance test results, RFI logs, issues logs, and so on, are we giving the building operator an “owner’s manual” or a “Technical Reference”? As stated earlier, we should be gathering the detailed project information for future reference; in the event of repairs, renovation/expansion, but the shelf of six, 4-inch ring binders is not a useful tool for most operations staff.

During the early stages of the project, it should be determined if a simplified “owner’s manual” would be useful to have provided by the project team at the close of construction. The essential nature of this manual is a distillation of the technical knowledge contained in all those binders into useful, easy-to-access information that is ready available to assist operators after the contractors have left the project and they are having to live with the building day-in and day-out.

It is not a dumbing-down of the complexity of the building system, but perhaps just an adjustment of the language and presentation. As in every industry, designers, programmers, and contractors develop a familiarity with certain terminology and procedures. It must be used for efficiency within the construction process – but for the end user, it can make certain information inaccessible.

LEED enhanced commissioning dictates that a systems manual is generated for the end user to perform this distillation function, unfortunately, the provider of the systems manual is usually someone from the design, contracting, or testing and balancing world and thus a “professional.” If there is a genuine focus to provide a document written in layman’s language, the passing on of the information can be that much smoother. The building owner has invested considerably in the physical capital that they receive in their completed building, they deserve quality in the intellectual capital delivered as well.

## **Conclusion**

We have seen through this paper that the Sequence of Operation plays a critical role from the beginning of the design process through owner occupation and beyond in communicating “How does (should) it all work?” Building a strong SOP early in the process, clarifying it and paying attention to it along the way, and following through in its transmittal to operations staff can positively impact the efficiency, persistence, and performance of the building systems.