SIMULATION-BASED APPROACHES FOR BUILDING CONTROL SYSTEM
DESIGN AND INTEGRATION

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ABSTRACT
This paper discusses how simulation-based approaches can improve the design of building control systems, with the goal of providing guidance to control system engineers for obtaining better control performance and more effective integration of the space conditioning components, equipment and systems. The discussion focuses on how to use simulation methods to improve the design and operation of the control system, including selection of models and tools, along with weather conditions, load profiles, time steps and the number and/or duration of simulations. Specific examples are implemented using detailed control modelling with HVACSIM+, to demonstrate and compare the modelling input requirements, level of detail, application of results and potential impact on control system design. The benefits of dynamic versus quasi-static simulations are discussed. Limitations in the methods, recommendations for appropriate applications, and suggestions for improvements are also described.

INTRODUCTION
The implementation of tightly integrated building systems and subsystems has been increasingly recognized as an essential factor in providing energy efficient, healthy and productive interior environments in buildings. This is particularly true for building control systems, which must bear the burden of controlling a wide array of components, equipment and systems to achieve energy efficient operation while also maintaining comfortable thermal conditions, and responding to occupant requirements. Generally, building space conditioning systems are designed to be able to meet peak thermal loads, the occurrences of which are relatively rare throughout a typical year. Most of the time, building systems operate at part-load conditions, which, if not properly accounted for, can have a significant impact on performance, frequently in a negative manner. This is because the part load efficiencies of the equipment and components comprising the systems are lower than at full load. In addition, building control systems need to provide adequate response to constantly varying environmental conditions and occupant factors. As thermal loads vary, the accuracy and stability of the control system also vary, leading to the possibility of loss of comfort control or increased energy consumption for space conditioning, or both.

Simulations can be useful in several respects for improving the design and integration of building control systems. The major responsibilities of the control system designer are to size and select control system components, determine control strategies, and specify control sequences. Typically, these choices are based on an analysis of a limited number of static design conditions. This process is inevitably coupled to the equipment and systems being controlled, such as heating and cooling coils, fans, pumps and thermal machinery. The control system designer may have had a hand in the design of the mechanical systems as well, or may be working in conjunction with the mechanical systems designer. Notably absent from the design process is a comprehensive evaluation of the part-load and dynamic performance of the control system, the results of which could suggest improvements and/or refinements in the design to achieve better overall performance. These improvements could include changes in equipment sizes and configurations, as well as control strategies.

This paper discusses how simulation-based approaches can be utilized to improve the design of building control systems, with the goal of providing guidance to control system engineers for obtaining better control performance and more effective integration of the space conditioning components, equipment and systems. The discussion focuses on how to use simulation methods to improve the design and operation of the control system, including selection of models and tools, along with weather conditions, load profiles, time steps and the number and/or duration of simulations. Specific examples are implemented using detailed control modeling with HVACSIM+, to demonstrate and compare the modeling input requirements, level of detail, application of results and potential impact on control system design. The benefits of dynamic versus quasi-static simulations are discussed. Limitations in the methods, recommendations for appropriate applications, and suggestions for improvements are also described.
LITERATURE SURVEY

The need for building control simulation is not newly articulated. Efforts have been underway since the early 1970’s to tackle the issue, but still tools are lacking that are efficient and effective for most designers. Most of the tools that are available are focused on the research community rather than the designers. Throughout the years, culminations of knowledge have led to a variety of tools and approaches. Haves, Norford, and DeSimone (1998) report on such effort supported by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). The research conducted and compiled was used to aid the capabilities of HVACSIM+ (Park, 2008) and TRNSYS.

Trčka & Hensen (2010) provide an overview of HVAC system modeling and simulation. Specifically regarding the controls, it is noted that there are few option for simulating more advanced controller functions. Approaches may require the simulation of supervisory control as with EnergyPlus down to local controllers in TRNSYS and ESP-r. As well, MATLAB and Dymola are noted for their ability to test controllers in simulations.

MATLAB and Modelica both exhibit capabilities of soundly modeling actual controllers and various tools and libraries are being developed to facilitate utilization of their potential. Riederer (2005) covers the developments of MATLAB/Simulink for building and HVAC simulation up to 2005, including SIMBAD, a MATLAB toolbox that facilitates building related simulations (Jreijiry, Inard, & Villeneuve, 2003). Likewise, the modeling language, Modelica, has garnered interest from the research community for its potential (Sahlin, Bring, & Eriksson, 2009; Wetter, 2009).

Ellis, Torcellini, and Crawley (2007), describe an energy management system module for EnergyPlus. The purpose is to enhance the control system simulation capability of EnergyPlus by facilitating more customizable supervisory control strategies. Emerging efforts are moving towards co-operative simulation environments with the goal of utilizing the capabilities of a host of different simulation tools. Wetter and Haves (2008) describe efforts to develop a middleware platform that would allow users to mesh the capabilities of various simulation programs in order to achieve more rapid and detailed models. In doing so, controllers may be modeled in an environment such as MATLAB and interact with EnergyPlus to control the simulated HVAC equipment. Likewise, co-simulation tools are being developed and evaluated for building performance simulation (Trčka, Hensen, & Wetter, 2009). The reported prototype system utilizes EnergyPlus and TRNSYS, making use of the advanced building models and large HVAC component library respectively.

Component-based simulation environments, like HVACSIM+, have also been utilized to evaluate building systems performance. Systems like this allow for more narrowly focused simulations that focus on building HVAC and other systems. Recently, Cui, Yang, Spitzer, and Fang (2008) use HVACSIM+ to simulate various performance comparisons for a hybrid ground-coupled heat pump with domestic hot water.

SIMULATION OF BUILDING CONTROL SYSTEMS

The use of simulation tools to help develop and evaluate building designs continues to increase in popularity as more user-friendly tools with greater capabilities are becoming available. Undoubtedly, the wide use of building simulation tools has resulted in an improvement in the energy performance of new buildings, and has enabled designers to investigate more innovative design alternatives. One key question that needs to be addressed, however, is how the simulations represent the actual performance of the systems being modeled, and how important this aspect is to effective design practices. Several recent investigations have shown that actual building energy consumption can differ markedly from simulation results, probably for a variety of reasons. This is particularly true for system configurations and operating strategies that differ from the more "typical" designs (i.e. the more “aggressive” design concepts). It is not always easy to determine the details of how different simulation tools handle the modeling of system components, and the detailed performance characteristics and interactions of building systems may not be incorporated in a comprehensive manner.

Simulation tools are composed of collections of models, schedules and material properties wrapped in a user interface and incorporating equation solving capabilities. All simulation tools will utilize assumptions and approximations to a greater or lesser extent; these assumptions may or may not have a significant impact on any conclusions drawn from a particular building simulation. This is especially true for control system simulations, since their operation is frequently modeled in an idealized fashion. For example, the response time of the control system and associated components may be ignored, as may be the impact of sensor location and actuator operation. These “real world” characteristics can have a noticeable effect on installed performance versus design intent.

The successful implementation of a building control system requires contributions from and cooperation among a number of disciplines. The process starts with the determination of the expectations of the owners, the needs of the occupants and the desired building functions and services, such as space conditioning, electrical power, illumination, safety, security, communication and entertainment. This, in
turn, leads to the initial design concepts for building envelope, mechanical and electrical systems. Since the purpose of the control system is to ensure the proper operation of building systems and to maintain the desired indoor environmental conditions (temperature, air quality, humidity, comfort), control system design is dependent on and tightly coupled to the design of the other building systems. As the building design process progresses, system concepts become more refined and more specific. Frequently, simulations are used to compare various design options and to evaluate building performance characteristics, such as energy usage, structural parameters and construction costs. Various simulation tools are available with varying degrees of ease of use, sophistication and application. Many of the issues motivating the use of building simulations involve the impact of design trade-offs or interactions, whereby the modification of one building system (i.e. envelope) affects another (i.e. heating and cooling). The broad goal of achieving integrated building design suggests a comprehensive analysis that incorporates the interactions between all of the relevant building systems. This approach would require some consideration of the operation of the control system.

The job of the building control system designer encompasses a range of activities, including:

- sizing and selecting actuators and control components
- selecting and locating sensors
- specifying a sequence of operation
- specifying setpoints
- developing schematic diagrams
- developing points lists

This collection of information is incorporated into bid documents, plans and submittals, eventually being instantiated as specific hardware and accompanying software elements which are installed, programmed and commissioned. Each of these steps presents an opportunity to utilize simulations to improve the final product: a properly functioning building control system. The nature and type of simulation are dependent on the stage in the process, the ambition of the project and the available time and resources. Simulations do require a certain amount of time and appropriate expertise, which may not always be available. Larger, more ambitious projects will afford more opportunity for design refinement and optimization.

One question regarding the simulation of building control systems is related to the type and duration of the simulation. Building energy simulations frequently are conducted on an annual basis using hourly increments and typical weather data files. While this type of simulation provides useful information regarding the effectiveness of general control and energy management strategies, it does not directly address other important control performance issues such as dynamic response and stability. In order to assess those aspects of building control systems it is necessary to conduct the simulation using much shorter time steps and with greater system detail. Fortunately, the duration of such short time step, detailed simulations does not have to be long; usually a few hours to a few days will suffice to reveal any performance issues that need to be remedied. Also, the specific weather data and other driving factors are not so important, so generic load profiles or arbitrary functions (impulse, step, ramp, square wave) can be used. These considerations allow the designer to focus more on the details of the control system and its specific components, including sensors, actuators, valves, dampers, coils, fans and pumps. Other important factors are the length of ducts and piping, and any associated transit times and time delays, along with actuator hysteresis, leakage, valve and damper authority, heat transfer and storage in fluid conduits, and temperature gradients.

In order to adequately address the control system design and performance issues outlined above, a simulation tool focused on building control systems can be utilized. It is not the intent of this paper to evaluate and compare the various software tools that are available for this purpose, but rather to discuss how they could be used, and to present some examples to demonstrate how the process would work. The example simulations were conducted using the HVACSIM+ computer program, which was developed at the National Institute of Standards and Technology specifically for modeling the performance of building control systems. While this program is very powerful and flexible, it is not commonly used by building designers, but is more of a research tool. However, it will suffice to demonstrate what could be done with a comprehensive building control system simulation tool given the proper combination of expertise, user interface and support.

**EXAMPLE SIMULATIONS**

Control system simulation can require quite a bit more detailed information than is typically used for building energy simulations. It may also require assumptions about set points and operating schedules. In order to illustrate this, a constant volume air handler for a single zone with a hydronic cooling coil was modeled using HVACSIM+, as shown in Figure 1. The model consisted of 24 components or units in the lexicon of HVACSIM+, as listed in Table 1. Each of the components has a specific set of parameters to describe their characteristics relevant to the simulation, including such things as physical dimensions, thermodynamic properties and mass flow values, some of which are also listed in the table. For these simulations, typical values were used that may not represent the best, but
could serve as starting points for refining a design. Some key points to note are the significant thermal capacitance of the supply air duct and conditioned zone, the time constants of the sensor and controller, and the valve actuator hysteresis. These characteristics will all combine to make it difficult to provide for stable control, as errors will tend to accumulate and control signals overcompensate.

Zone loads and outdoor air temperature were explicitly specified, and other variables or set points were selected or modified to suit each simulation using a boundary value file. The model includes a total of 66 variables (21 pressure, 21 temperature, 6 flow, 10 control, 6 power and 4 others). HVAVSIM+ solves for the values of all dependent variables for each time step based on physical models of components and the fundamental principles underlying heat and mass transfer. Many aspects of

Figure 1. Schematic of single zone air handler
the simulation, such as initial values, time steps and output data can be specified by the user. Each simulation needs to have a starting condition. Sometimes, these types of simulations are started with all variables set to zero, but for building control system modeling, this approach may not work as the numerical solver may not converge to the correct solution. Starting with initial values in the general ballpark of final values will usually be beneficial in encouraging a convergent solution, but numerical challenges will sometimes present themselves regardless.

For a transient simulation, it is useful to start by simulating an equilibrium condition before moving into the transient boundary condition, thereby allowing the control system to attain a good operating state before having to respond to the test condition. Then, the test condition can be applied, either as a onetime event (step change, ramp or pulse) or as a steady periodic profile (sinusoidal, cyclic) change in one or more boundary variables (setpoints, outdoor air temperature, heat gain, etc.). Variables of interest, such as space temperatures, thermal loads and control signals, can be output from the simulation and plotted for analysis.

For the first example, a constant zone load was simulated. This is useful for verifying the sizing of the components identifying any modeling errors and checking the execution of the simulation. For this model, the chilled water valve on the cooling coil is controlled by the room air temperature, which modulates the flow of chilled water through the cooling coil to try to maintain the zone air temperature at its setpoint. Figure 2a shows zone air temperature and cooling load for a steady zone heat gain of 12 kW simulated over approximately one day. The initial cyclic behavior is a consequence of the models converging to an equilibrium condition from the initial condition. The zone temperature then stabilizes as the room cooling load drifts slowly higher to compensate for heat storage and loss from the ducts and zone. The cooling load of 50 kW (coil load) includes both sensible and latent loads from the zone heat gain and outdoor makeup air, as well as heat gains from the fans and ducts. This well is above the simple loads due to zone heat gain and ventilation air. Figure 3 shows the control signal from the controller to the control valve, and the chilled water supply temperature, the latter of which

![Figure 2](image-url)

Figure 2. Zone air temperature and cooling load for a steady heat gain of 12 kW (a), 8 kW (b), and 4 kW (c)
is being held constant. The control signal and valve seem to be operating properly.

Figure 3. Chilled water supply temperature and control signal to valve for a steady zone heat gain of 12 kW.

Similar simulation was conducted for steady zone heat gains of 8 and 4 kW, as shown in Figures 2b and 2c. For the 8 kW case, the simulation takes a bit longer to reach equilibrium, but then both zone air temperature and cooling load stabilize as expected. However, for the 4 kW case, oscillating behavior is observed for the entire simulation time. It is not immediately apparent whether this is due to a numerical problem or a system problem. In other words, is the control system itself oscillating due to the tuning of the PI controller and other factors, or is the numerical solver of the simulation tool failing to converge to the correct solution. It may be that a combination of the two factors are actually responsible, as when the physical system becomes unstable or approaches instability, the numerical solution becomes more difficult. In this case, it is

Table 1 Components of Example Control System Simulation

<table>
<thead>
<tr>
<th>Unit Number</th>
<th>Component and Selected Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inlet pipe to coil V=0.00251 m³ C=2.277 kJ/C</td>
</tr>
<tr>
<td>2</td>
<td>Bypass pipe V=0.00023 m³ C=0.2116 kJ/C</td>
</tr>
<tr>
<td>3</td>
<td>Outlet pipe from coil V=0.002278 m³ C=2.07 kJ/C</td>
</tr>
<tr>
<td>4</td>
<td>Three-way valve τ=10 s hysteresis = 0.10</td>
</tr>
<tr>
<td>5</td>
<td>Return pipe V=0.0355 m³ C=32.2 kJ/C</td>
</tr>
<tr>
<td>6</td>
<td>Air temperature sensor τ= 20 s</td>
</tr>
<tr>
<td>7</td>
<td>PID controller K_P=6.0 K_I=0.08 τ=2 s</td>
</tr>
<tr>
<td>8</td>
<td>Cooling coil C=34.669 m³</td>
</tr>
<tr>
<td>9</td>
<td>Control signal inverter</td>
</tr>
<tr>
<td>10</td>
<td>Return fan Pressure/flow coefficients</td>
</tr>
<tr>
<td>11</td>
<td>Duct</td>
</tr>
<tr>
<td>12</td>
<td>Flow split</td>
</tr>
<tr>
<td>13</td>
<td>Exhaust air damper Leakage 0.012</td>
</tr>
<tr>
<td>14</td>
<td>Recirculation air damper Leakage 0.012</td>
</tr>
<tr>
<td>15</td>
<td>Mixing box</td>
</tr>
<tr>
<td>16</td>
<td>Outdoor air damper Leakage 0.012</td>
</tr>
<tr>
<td>17</td>
<td>Outdoor air duct</td>
</tr>
<tr>
<td>18</td>
<td>Damper (filter flow resistance)</td>
</tr>
<tr>
<td>19</td>
<td>Damper (heating coil flow resistance)</td>
</tr>
<tr>
<td>20</td>
<td>Damper (cooling coil flow resistance)</td>
</tr>
<tr>
<td>21</td>
<td>Supply fan Pressure/flow coefficients</td>
</tr>
<tr>
<td>22</td>
<td>Supply air duct C=220.0 kJ/C V=7.75 m³</td>
</tr>
<tr>
<td>23</td>
<td>Conditioned zone V=1440 m³ C_{EXT}=40000 kJ/C C_{INT}=4000 kJ/C</td>
</tr>
</tbody>
</table>
likely that the physical system itself is at least partially responsible, since equilibrium was achieved at the higher load conditions. This would suggest investigating the gains for the PI controller, and the effects of the various time constants.

It is not the intent of this paper to try to optimize this particular example system, but rather to explore the use of simulations to design control systems. Thus, we will continue with the example by implementing variable zone heat gain and outdoor air temperature to look at the impact on zone air temperature and cooling load.

Figure 4 shows a variable heat gain profile and Figure 5 shows the resulting zone air temperature and cooling load, which appear to be acceptable (i.e., zone air temperature tracks the setpoint and cooling loads are smooth).

Figure 6 shows sensible cooling for the variable zone heat gain profile.

Figure 7 shows supply air temperature for the variable zone heat gain profile.

CONCLUSION

Detailed simulations of building control systems can be useful for designing, refining and verifying the performance of the systems under realistic operating conditions, provided that sufficient information is available to accurately model the components. Although not a simple task, evaluating the effects of time constants, thermal storage, hysteresis and heat loss can identify performance issues that otherwise might be overlooked. However, simulation tools with these capabilities are generally lacking, particularly for building control system designers. The current emphasis on simulation tool development may help to overcome this barrier and enable more realistic performance evaluations of building control systems, thereby promoting the design of better building control systems and more energy efficient and comfortable buildings.

REFERENCES

with domestic hot water heating systems using HVACSIM+. Energy and Buildings, 40(9), 1731-1736.


