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Mixed Mode Simulation Tools

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1. OBJECTIVES

This project is intended to facilitate communication between researchers and practitioners about how tools available for simulating mixed mode (MM) and naturally ventilated (NV) buildings are currently being used by practitioners, and what new functionality is most critical for future tool development. The primary goal of the project is to understand how practitioners currently approach simulating MM and NV buildings, including the assumptions and inputs they use, their methodologies, and their preferred tools. We also provide a brief methods-based overview of the research literature on simulating MM and NV buildings, with the hope that practitioners can learn from researchers' approaches.

2. BACKGROUND

There is no definitive guide to modeling NV and MM buildings in the research or practicing communities. The methods described in published literature vary greatly from study to study, while the methods employed by energy modelers in practice differ from firm to firm and person to person as time, budget, analyst experience, and client needs change from project to project.

This paper provides insight into the differences and similarities of methods used by a cross-section of energy modeling practitioners. It is not intended to be a comprehensive review of software tools, or an explicit guide to modeling NV and MM buildings. Instead, this is a survey of current modeling approaches used by the nineteen energy modeling practitioners and tool developers we interviewed. Our goals are to identify which methods are currently being used to evaluate performance and design of NV and MM buildings, and how these methods varied by practitioner, firm, project type, project goal, location, and building type. This paper provides a summary of the information collected during these interviews, including tool developments that practitioners would like to see in the near future as a way to help identify where researchers might next turn their attention to.

In addition to the results from the interviews, this paper also provides a literature review to compare and contrast the methods and resources used by researchers with those used by practitioners. Our goal is to highlight areas where practitioners may benefit from work conducted by researchers and to provide resources to assist in simulating NV and MM buildings.

3. ABSTRACT

This project was focused on bridging the gap between researchers and practitioners interested in simulation methods for naturally-ventilated and mixed mode buildings. In a focused literature review we outlined information on modeling tools and methods used by researchers, including early design phase appropriate tools, the importance of site-specific wind data and accurate wind pressure coefficients, and existing and future integrated tool options. We also provided an overview of research on window opening behavior, noting that there is still little practical guidance for practitioners interested in stochastic modeling techniques. In the second section of the paper we provided results from interviews with practitioners who model naturally-ventilated and mixed mode buildings. We found that simulation methods vary widely by practitioner and project, with limited consensus on the best simulation tools and modeling techniques. Practitioners reported that they would like to see more integrated tools, tools with improved result visualizations, and early-phase design tools.

4. METHODS

This project began with a literature review focused on NV and MM simulation methods to create a framework to understand the kinds of tools and methods currently in use by researchers in this field. This was a starting point to understand what are the most important aspects of modeling NV and MM buildings. We focused on software tools and critical modeling inputs such as weather data and window opening behavior.

Next we conducted an early survey of CBE partners to get a broad sense of the industry (see Appendix A for a copy of the survey). We wanted to identify the different tools practitioners were using and how these tools differed from one another. For example, we wanted to know if practitioners tended to gravitate towards a certain type of tool, e.g. bulk airflow modeling, or if they used a variety.

The answers we received from the survey, in addition to the preliminary literature review, helped us establish an understanding of what types of questions we would need to ask practitioners during the interview portion of the study. To identify practitioners we began by asking for volunteers from the October 2013 CBE meeting. We targeted practitioners who conducted energy modeling work themselves and had experience modeling NV and MM buildings. We also consulted national awards lists (e.g. past AIA COTE Top Ten winners) to identify other firms who had worked on NV and MM projects, especially those located outside of California and the U.S. West Coast. As part of the interview process with these early respondents we asked for recommendations of other firms and practitioners who would have the kind of experience we were looking for.

During the interviews, we asked respondents to answer our questions with reference to their NV and MM projects only. We started with general questions about where their projects were located and what major reasons they had for modeling NV and MM buildings. We then asked specifically about the software tools they used, if these tools differed depending on the phase of design, and how they made their tool selection. We developed specific questions for different types of tools each respondent might have used, to learn about the assumptions and inputs they used. We followed up with a discussion of the strengths and limitations of their tools, and what further developments would be beneficial in the future. Lastly, we asked several open-ended questions about their project work to find out about when modeling NV and MM led to particular success on a project, or where they encountered unexpected results or findings related to modeling. See Appendix B for the full list of interview questions.

5. LITERATURE REVIEW

This literature review provides a selective overview of the modeling tools and approaches used by researchers when modeling mixed mode and naturally ventilated buildings. Not surprisingly, most literature is from researchers written for a similar research audience, rather than for practitioners. This section is intended to be a resource for practitioners interested in exploring techniques and methods used in research, but currently lacking the resources for such a literature review. With this in mind, we focused our attention on the variety of modeling tools described in the literature, sources for inputs that are especially influential to the results, and early phase simulation tools. A comprehensive literature review of all the techniques currently in use, or of the technical capabilities of the tools itself, is outside the scope of this project.

5.1 Overview of modeling tools and methods

Types of tools
The modeling methods described in the literature for mixed mode and naturally ventilated buildings are diverse. The three general categories of methods researchers are using include standalone airflow network tools such as CONTAMW (Blomsterberg & Johansson 2005), airflow network models coupled with thermal modeling tools such as COMIS and TRNSYS (Bradley & Utzinger 2007), and computational fluid dynamics (CFD) tools like Airpak (Dong et al. 2010).

In comparing different categories of tools, bulk airflow tools were cited in the literature as reasonably accurate and preferable to CFD because they were less time-consuming to use and required less detail for inputs such as precise boundary conditions (Bradley & Utzinger 2007). However, it was also noted that the most difficult part of using bulk airflow tools was providing sufficiently accurate inputs to the tool, e.g. wind pressure coefficients (Blomsterberg & Johannson 2005).

In 2008 Crawley et. al published a comparison of twenty building energy simulation programs, including EnergyPlus, IES VE, Tas, and TRNSYS. Among other topics, this study compared the capability of the tools to calculate wind pressure coefficients, model natural ventilation and mixed mode ventilation, and to control window openings based on internal or external conditions (Crawley et al. 2008). At the time of this writing an update to this report was underway and was anticipated to be completed in 2015.

Tool integration
A common challenge in practice is the inability of different simulation tools to interact or integrate with one another, especially building energy simulation tools with airflow network and CFD tools. In the literature we have found a few examples of tools that can be integrated, namely TRNSYS and EnergyPlus with airflow network tools or CFD packages.

TRNSYS is a transient systems building energy simulation program. Within TRNSYS, a system is defined as a set of connected components. This modular structure means that components may be sourced from the standard library or be coded by users (A TRaNsient SYstems Simulation Program 2013). Due to this flexible design, standard components have been developed for TRNSYS that allow it to interface with airflow tools like COMIS and CONTAM (Additional Resources 2013 and CONTAM 2013), and the CFD package FLUENT (Arias 2006).

EnergyPlus already has an embedded Airflow Network object to model natural ventilation. This allows for a coupling of thermal and airflow effects within a single tool. This object is the successor to a previous link with the external program COMIS (Gu 2007). Zhai and Chen (2005) developed a program to link EnergyPlus with a CFD package and found that coupling the two provides more accurate results than the individual simulations because the CFD simulation was able to use updated and real-time boundary conditions from EnergyPlus and in turn could provide more accurate convective heat information to allow EnergyPlus to more accurately calculate energy use and envelope performance. Despite these advantages, the authors felt that the extensive computing time limited the widespread applicability of coupling the two tools together in practice (Zhai & Chen, 2005). With the improvement in computer power since, it is possible that this barrier no longer exists, but a more recent study was not identified.

There is promising research underway for other methods of integrating different types of tools. The current applicability of these tools is limited to research applications due to their heavy programming requirements. Modelica is an object-oriented modeling language for modeling physical systems. In 2006 Wetter described a library of multizone airflow models for use in Modelica to model interzonal airflows due to buoyancy effects, temperature differentials, flow imbalances, and external wind pressures. These models may be used in conjunction with existing HVAC and thermal models for an integrated simulation (Wetter 2006). Another method being developed is to standardize information exchange. The Functional Mockup Interface (FMI) is a tool-independent standard developed to exchange information between tools and support co-simulation of models (Functional Mock-up Interface 2014). Originally developed for automotive simulations, it is now supported by over 35 tools, including energy simulation tools like EnergyPlus. For use in co-simulation, Nouidui (2014) coupled an HVAC model from Modelica with a room model in EnergyPlus, where each environment produced outputs that were fed as inputs into the other. The paper found FMI to be a robust and promising approach and suggested that future work examine the performance differences of co-simulation and simulating in a single environment (Nouidui 2014). Similarly to how other simulation software started out as research-oriented before making their way into practice, it is reasonable to consider that these methods may follow suit in due time.

Thermal comfort

Modeling the performance of buildings ultimately must include an assessment of whether the indoor conditions are thermally comfortable. The two methods cited in the literature for evaluating thermal comfort include the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) model, or the adaptive comfort model, both of which are outlined in ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy (ASHRAE 2010). The adaptive comfort model is defined in the standard with specific limits on its applicability. In addition to metabolic rate, clothing level, and outdoor temperature limits, this model is defined to only apply to buildings without mechanical cooling systems (and no operating heating system) where occupants control the operable windows (ASHRAE 2010). Despite these defined limitations, one instance was found in the literature where researchers used the adaptive comfort model in mixed mode buildings (Borgeson 2010), and while there seems to be much anecdotal evidence that it is being used, no other examples have been identified in the literature.

A recent addition to the ASHRAE 55 standard that is relevant for NV and MM buildings are new guidelines for calculating thermal comfort at elevated air speeds (ASHRAE 2010). For metabolic rate and clo values within specified limits, the standard defines acceptable ranges of operative temperatures at air speeds between 0.15 m/s (30 fpm) and 1.2 m/s (236 fpm). Arens et al. (2009) analyzed additional data from office field studies demonstrating that occupants generally want more air speed in neutral and warm environments. This added provision in the standard can allow designers to utilize natural ventilation and mixed mode systems to maintain thermal comfort at higher operative temperatures by providing elevated air speeds. Using the online CBE Thermal Comfort Tool, which is compliant with ASHRAE 55-2010, users can calculate exactly how far the comfort range can be extended to at different air speeds (Hoyt et al. 2013).

5.2 Source of inputs for models

Several key modeling inputs for mixed mode and naturally ventilated models have been identified in the literature. For wind-driven ventilation, wind speed, direction, and pressure coefficients are critical components to be considered in the simulations. For both wind- and buoyancy-driven ventilation for buildings with occupant-controlled window openings, occupant window opening behavior is another influential input.

Weather data
Weather data is an important input in natural ventilation simulations, especially when modeling wind-driven scenarios. We could not identify any literature that studied the relevance of airport wind speed and direction data to site-specific circumstances, so instead we investigated how sensitive the airflow analysis is to the provided wind information in order to understand the importance of site-specific data.

Stavrakakis et al. (2008) studied the influence of wind data in a sensitivity analysis for a study on cross-ventilation, comparing the effect of various input values for terrain roughness, wind speed, and wind angle of incidence. They concluded that there was no significant difference in the results of their analyses (i.e., the indoor environmental conditions) for flat vs. rural terrain roughness, a variation of +/-10% in wind speed, or a difference of +/-15% in wind angle of incidence. Accurate wind data was also stressed by Zhai et al. (2011), who recommend using on-site measured temperature, wind, and solar conditions for more accurate modeling results, and Belleri et al. (2014) who found that the wind speed profile was the most influential parameter in an EnergyPlus airflow network model after occupant behavior.

In our research we found one software tool that offers interpolated weather data for any site around the world, Meteonorm (Remund et al. 2014). The software is focused on providing values for irradiation and temperature, and where data is not available, it calculates hourly values from monthly averages using a stochastic model. The handbook for version 7.1 states that wind speed is interpolated using monthly averages of the nearest weather stations in combination with user inputs about local terrain conditions. No validation of the wind data generation accuracy of Meteonorm has been found in the literature.

In general, we found no studies in the literature examining the accuracy of extrapolating wind speed or direction data in order to obtain site-specific conditions, although there are multiple studies that have tried to do the same for other parameters such as dry bulb temperature and solar radiation. As wind speed and direction can vary greatly from local weather station values due to local terrain and microclimates, this is an area that warrants further investigating.

Wind pressure coefficients
Wind pressure coefficients are a significant source of uncertainty in building energy simulations and airflow network models (Belleri et al. 2014, de Wit & Augenbroe 2001, Hensen 1991, Knoll et al. 1995, and Tuomaala 2002). In a study of a school in Sweden, Blomsterberg & Johansson (2005) found that a CONTAMW-based study was particularly sensitive to wind pressure coefficients they used, which were derived from wind tunnel tests.

Wind tunnel testing is just one source of wind pressure coefficients. Along with full-scale Modeling and CFD analysis, wind tunnel testing is considered a primary source of wind pressure; secondary sources include published databases and analytical models (Cóstola 2009). Primary methods are typically limited to use in research rather than practice, due to the time-consuming methods and level of skill required. Primary sources are considered more accurate than secondary sources, however even among the three primary sources, resultant data is not always entirely reproducible, as differences in the calibration of models, and skill levels of operators and researchers can affect the results. (Cóstola 2009).

Under secondary sources, the two main databases in use are those provided by the Air Infiltration and Ventilation Center (AIVC) (Orme & Leksmono 2002) and ASHRAE in the ASHRAE Handbook of Fundamentals (ASHRAE 2013). The AIVC tables include wind pressure coefficients for open, semi-exposed and sheltered low-rise buildings based on multiple wind tunnel studies, while their high-rise building data are based on a single source (Cóstola 2009). In the 2013 version of ASHRAE Fundamentals, Chapter 24 *Airflow Around Buildings* provides guidance for pressure coefficients for low- and high-rise buildings, but does not consider sheltered buildings.

The three main analytical models found for wind pressure coefficients include one developed by Swami and Chandra (1987), CpCalc+ which was developed within COMIS (Cóstola 2009), and CpGenerator (Cp Generator 2013). The Swami and Chandra model uses one equation for low-rise buildings and one equation for high-rise buildings, taking as inputs the angle of incidence, a normalized pressure coefficient, and a floor plan aspect ratio. This method does not take sheltering into account. Building on this existing model, the algorithm used in CpCalc+ added the effects of sheltering, while the more recently developed CpGenerator was designed to have an even more improved sheltering calculation (Cóstola 2009). At the time of this writing, CpGenerator was the only analytical model with a current website and technical support.

A study by Belleri et al. (2014) compared wind pressure coefficients from multiple sources and found that for rectangular buildings with regular surroundings, databases provide sufficient accuracy, however for buildings with irregular surroundings, the coefficients estimated by CpGenerator were closer to those measured in wind tunnels than the database-sourced values because CpGenerator models include the surrounding buildings. This is particularly important for practitioners because real buildings always have to contend with the site conditions and local terrain, whereas in research these are not always considered.

Window opening behavior

Window operation behavior can have a significant impact on how well natural ventilation designs actually ventilate and condition spaces, but it is also an area with much uncertainty. There has been a large amount of research studying occupant behavior in existing buildings and correlating their window operation patterns with different variables, from indoor and outdoor temperature to rain and façade orientation. The literature consists primarily of researchers writing for an audience of other researchers, or perhaps tool developers, but often not for practitioners. This means that although there is a large body of work studying and correlating occupant behavior to physical and non-physical parameters, there is limited information or guidance about implementing improved algorithms in software based on these results. In this section we provide a guide to the most influential factors and recommend that researchers specifically consider practitioners as an important audience in future work in this subject.

The literature on occupant window operation behavior primarily includes studies linking window opening behavior to obvious variables such as indoor temperature, outdoor temperature, indoor air quality, and the need for "fresh air." Other studies looked at the relationship between window opening behavior and wind, rain, and season, as well as less obvious potential influences such as the façade orientation, type of window, and number of occupants with access to the same window. The overall conclusion drawn from these studies is that occupant behavior is stochastic, i.e., there is an element of probability involved because behavior cannot be predicted in a repeatable manner.

A number of studies have identified a connection between window opening behavior and indoor temperature (Dutton et al. 2008, Haldi & Robinson 2008, Inkarojrit & Paliaga 2004, Pfafferott & Herkel 2007, Rijal et al. 2007, and Yun & Steemers 2008), while other studies demonstrated a link between behavior and outdoor temperature (Brundrett 1977, Dick & Thomas 1951, Fritsch et al. 1990, Lyberg 1981, and Warren & Parkins 1984). Several studies found evidence that window opening and closing behavior are not correlated at the same strengths to the same variables. For example, Haldi and Robinson (2008) found that window opening actions were linked to indoor variables, while window closing actions were linked to both indoor and outdoor variables. The results of a study conducted by Rijal et al. (2007) concurred, finding that the percentage of open windows was dependent on both indoor and outdoor temperatures.

In addition to these physical variables, social influences and habits also play a role in how windows are operated. Haldi and Robinson (2009) found that the number of occupants responsible for a window affected that window's operation, and that behavior could be attributed to the most active occupant, rather than a concert of actions among all occupants. Window operation was also found to be correlated to arrival and departure times of occupants (Haldi & Robinson 2008, Haldi & Robinson 2009, Herkel et al. 2008, Pfafferott & Herkel 2007, and Yun & Steemers 2008). While this result may appear obvious, it is important to note that multiple non-physical parameters (i.e., those that do not relate to thermal comfort) may affect window operation.

In another example, occupants were shown to be influenced by their desire for a connection to the outdoors (Heerwagen J & Heerwagen D 1986 and Heerwagen & Zagreus 2005). Façade orientation was also linked to percentage of open windows, with south-facing windows 30% more likely to be open than those found on other façades (Inkarojrit & Paliaga 2004 and Zhang & Barrett 2011). It was also found that the type of window could affect operation patterns, as some operable windows offered more protection from wind or rain, or allowed more control over effective opening size (Roetzel et al. 2010). It is expected that seasons would have an effect on window operation; however, studies have shown that occupants open windows even during the heating season for ventilation purposes (Dick & Thomas 1951, Fritsch et al. 1990, Rubin et al. 1978, and Warren & Parkins 1984).

With so many variables affecting how occupants operate windows, multiple studies have concluded a stochastic model is the best representation of occupant behavior (Ackerly & Brager 2011, Belleri 2013, Borgeson & Brager 2008, Clarke et al. 2006, Dutton et al. 2012, and Gunay 2013). Based on this conclusion, Rijal et al. (2007) developed an adaptive window algorithm to predict occupant behavior, based on outdoor temperature, comfort temperatures, indoor temperatures, and probability functions, and the observed assumption that occupants operate windows in order to reduce their own discomfort. Haldi and Robinson (2009) outlined another algorithm using a flow chart to predict window operation behavior based on occupancy, current window status, arrival and departure times of occupants, outdoor temperature, and presence of rain. Further development of stochastic algorithms that can be implemented by practitioners in existing software is needed.

5.3 Early phase simulation tools

Tools that can be used early in the design of naturally ventilated and mixed mode buildings can help users determine which particular design strategies most strongly influence energy use and comfort, and should be investigated in more detail in later stages of design. We have found multiple tools that may be used to determine natural ventilation feasibility when specific design decisions have not yet been made.

The National Institute of Standards and Technology (NIST) has produced two tools that may be used during early design, the Climate Suitability Tool and LoopDA (Available Software Tools 2014). The Climate Suitability Tool was developed to provide preliminary guidance to designers on ventilation levels required for daytime and nighttime cooling strategies (Emmerich et al. 2011). The user provides the tool with inputs such as weather file, internal heat gains, minimum ventilation rate (e.g. from ASHRAE 62.1), ceiling height, natural ventilation parameters, and cooling and heating setpoints. The tool calculates the direct cooling (i.e., naturally ventilating when needed) and the night cooling potential (as percent of days, annually, when natural ventilation can satisfy cooling needs), based on the setpoints provided by the user and the adaptive comfort model (Climate Suitability Tool 2012). Using a single-zone thermal model and hourly weather data, the tool computes thermal comfort using ASHRAE 55, including the adaptive comfort model (Emmerich et al. 2011).

LoopDA is based on the Loop Equation Design Method and runs on CONTAM's simulation engine. It is the only tool found that calculates required opening area based on a specified desired air flow rate, rather than the other way around. In the LoopDA interface, users create a line drawing of the zones of the building in elevation. Each zone is defined with a minimum required ventilation rate and thermal characteristics. Airflow paths (e.g. ducts) are drawn in to connect zones to each other. A calculation is performed to determine the minimum opening area required based on the desired air flow rates entered (Dols et al. 2012).

Another tool, COMFEN 4.1, has the ability to model buoyancy-driven natural ventilation in a single-sided zones. When selected, COMFEN will model the zone without mechanical cooling, i.e., it does not model mixed mode operation. Users can change the type of operable window (e.g., awning, casement) and openable area for each window. COMFEN provides a heat map of the entire year, indicating the total numbers of hours the cooling set point is not met with natural ventilation. Future development of the tool is expected to include adaptive comfort results, cross-ventilation, and the ability to add internal thermal mass (COMFEN 4.1 Beta Release Notes 2014). For practitioners, there will rarely be situations that meet the assumptions and limits that COMFEN imposes (e.g. single exposure), so its relevance and applicability may be limited.

MIT's CoolVent tool allows designers to analyze different natural ventilation schemes over a 24 hour period or at a specific instance in time. It can model single-sided, cross, central atrium, and side atrium ventilation. Users input internal gains, information about the building dimensions, opening dimensions and locations, and ventilation strategies such as thermal mass, night cooling and different types of window control. The tool provides a visualization of the temperatures and flow rates in the space over the course of the day, a plot of the daily temperature variation, air stratification, and thermal comfort results based on ASHRAE or user-defined ranges. The tool can also model fan-assisted natural ventilation and will provide fan energy use as a result (Getting Started 2014). Initially developed as a doctoral thesis (Tan 2005), the tool has been analyzed as an early design tool, and has since been used to design the natural ventilation systems of the HULIC headquarters in Tokyo (Menchaca-Brandan et al. 2012), and has been updated with new capabilities, such as implementing thermal stratification profiles (Menchaca-Brandan 2012).

MIT has another early phase design tool intended to help architects quickly determine which design parameters can save the most energy while still preserving occupant comfort. The online tool, Design Advisor, analyzes energy use, comfort, and daylighting potential in addition to natural ventilation (MIT Design Advisor 2009). Validation of the tool has been conducted, comparing annual and monthly load calculations against EnergyPlus models, demonstrating that Design Advisor can produce reasonable results in agreement with results from EnergyPlus (Urban and Glicksman, 2007).

6. INTERVIEW RESULTS

In total, seventeen practitioners and two tool developers were interviewed for this study, all at various levels of management within their firms. Of the practitioners, fifteen currently work or previously worked on the U.S. and Canadian West Coast while two were based in other U.S. locations. Four currently or previously worked in Europe, including England, Wales and Germany. Two of the practitioners interviewed worked for architecture or design firms, while the rest worked for self-described engineering or building performance consulting firms.

Practitioners reported where most of their NV and MM projects were. Eight reported working on projects in the San Francisco Bay Area, while fourteen worked on projects elsewhere on the U.S. West Coast. Also represented were projects across the United States in Hawaii, the Rocky Mountains, the Midwest, and East Coast. Internationally, practitioners reported working on projects in Canada, Australia, China, India, Wales, England, Germany, and Syria, as well.

The most common building types reported were offices (13 practitioners), university or higher education buildings (12 practitioners), and K-12 schools (9 practitioners). At least four practitioners reported analyzing NV or MM systems for high-rise residential projects, sports facilities, and government and civic buildings. Also represented were auditoriums, hospitals, libraries, retail, laboratories, and convention centers.

6.1 Findings: General approaches to simulation

The practitioners interviewed gave multiple reasons when and why they used simulation tools for their NV and MM analysis work. Interestingly, practitioners reported that they did not always consider modeling as an essential step in the NV and MM design process because the natural ventilation strategy was not always critical to achieving thermal comfort (e.g. a backup mechanical system was in place) or was not considered a significant contributor to the performance goals of the project (e.g. it was too difficult to demonstrate the contribution to energy savings for LEED certification). One practitioner reported that he did not typically model NV for small spaces due to his past experience, stating that for small spaces sufficient airflow is typically not difficult to achieve even with small openings. When NV and MM systems were modeled, practitioners were most often interested in evaluating the feasibility of maintaining thermal comfort for occupants, rather than demonstrating potential energy savings.

Twelve practitioners reported that the main reasons they conducted modeling were to evaluate design features in terms of the natural ventilation driving mechanism (e.g., wind or buoyancy-driven), façade performance, window area, orientation, and air flow paths. Nine respondents stated that investigating thermal comfort was a key driver of their work. More specifically, they calculated the number of hours, annually, when thermal comfort could be achieved through natural ventilation, in many cases using the adaptive comfort model in ASHRAE 55 as a guide. The final significant reason cited for modeling was to determine energy performance; five respondents stated that calculating energy savings with respect to code or LEED compliance was the primary reason they conducted NV and MM simulations. However, one practitioner stated that for a mixed mode high school in San Francisco, modeling to prove the building would operate as designed to satisfy LEED requirements was more complicated and time consuming than his team could afford on that project, so they modeled the building without NV for LEED purposes.

Practitioners were interested in obtaining different kinds of information during the various phases of design. In general, they preferred to be involved with a project as early as possible in order to influence key parameters such as massing, window locations and sizes, and shaft sizing. The interviews revealed that phase-by-phase modeling goals depend heavily on the project's overall goals, and when the modelers and analysts were brought on board.

For example, studies based on an analysis of site weather trends, including temperature and relative humidity, were more heavily concentrated towards the beginning of the design process, in concept or schematic design. Practitioners used these early feasibility studies to investigate the potential number of hours annually when achieving thermal comfort is possible. Investigating thermal comfort was often periodically revisited in more detail during later phases.

Practitioners reported that exploring the integration of natural ventilation with the building's HVAC systems typically started in schematic design, when they were also investigating the details of the airflow pathways and window sizing. Full integration of passive and active strategies were more detailed during design development. For projects that used simulation to demonstrate compliance with energy-related codes or LEED credits, compliance status was evaluated at each phase, including how natural ventilation affected overall energy use.

6.2 Findings: Tool selection

Practitioners reported both technical and non-technical reasons for why they selected a particular simulation tool. Unsurprisingly, the most often cited reason was that, in their opinion, the software was simply the right tool for the job, which depended on what their particular goal was to begin with (e.g. it might be selected because it was the best bulk air flow analysis software tool available). The other most common reasons cited were all non-technical. Ease of use was an important aspect, both being able to quickly learn how to use the tool, and using tools that team members were already familiar with. The third most common reason was circumstantial - they happened to have an opportunity to use a particular tool based on project type. For example, two practitioners stated that they had an opportunity to try out a new tool on a specific project due to availability, and they kept using it afterward because of its success. And another practitioner said that the tools they used were region-specific based on local code compliance regulations.

Practitioners also cited budget as a non-technical reason for selecting particular tools. Tools that were more time-consuming to use were limited to projects with larger resources. The remaining reasons cited were both technical and only reported by three practitioners: compatibility with other software tools used (e.g. whole building energy modeling or CAD tool), reliability of software based on access (open source vs. proprietary tools), and availability of technical support by the tool developer.

6.3 Findings: Tool-specific feedback

This part of the study asked each practitioner to report which simulation tools they used and in which manner. Practitioners discussed their use of different bulk airflow modeling tools and CFD software. In all, more than fifteen different tools were cited, including EnergyPlus, IES Virtual Environment, Tas, eQUEST, CONTAM, TRNSYS, and numerous CFD tools. The following is a summary of how the practitioners interviewed reporting using the tool, with their opinions on strengths and limitations, as well as specific examples where the tool particularly excelled or helped them in their analysis.

Bulk airflow modeling tools

Bulk airflow modeling tools were the most often cited as being regularly used by the practitioners interviewed, and included: EnergyPlus' Airflow Network, IES' Macroflo module, Tas, TRNFLOW (COMIS integrated with TRNSYS), and CONTAM. Practitioners reported success with bulk airflow tools, and in multiple cases were able to verify the accuracy of their model with post-construction monitoring. For example, in a higher education building in California, one practitioner reported that the airflow rates provided by a passive downdraft tower were found to be accurately predicted in their Tas model when compared to measurements with airflow sensors post-construction. In another case, the use of bulk airflow modeling allowed another higher education building in California to gain an exemption from the Title 24 natural ventilation requirement of a minimum 4% glazing to floor area ratio. Using the modeling tool, the team was able to prove that a ratio of 2% would be sufficient to meet the ventilation needs of the space and occupants. One practitioner even reported convincing the owner to completely remove the backup mechanical cooling system for a school in southern California, after demonstrating with a bulk airflow model the minimal number of hours per year that the building's internal temperature would fall above the comfort range with only natural ventilation.

IES Virtual Environment (VE) was one of the most cited tools among the practitioners we interviewed. Of the nine who reported using it, seven used the Macroflo module (bulk airflow-based) and three used the Microflo module (CFD-based). Practitioners used IES VE primarily to evaluate design alternatives and calculate the annual percentage of hours that natural ventilation is possible. Two practitioners reported using IES VE for their whole building energy model and said being able to use one tool for both purposes was an important benefit. In an IES model for a Canadian net-zero energy visitor center with a solar chimney, one practitioner found that the backup cooling was running for only a minimal number of hours. Using the model his team adjusted the orientation in order to remove the need for the cooling system altogether. Although the cooling system was included in the final design, in the more than two years since the opening of the building, the practitioner reported that the backup system had yet to be used.

In general, practitioners reported positively about IES VE's user interface, accuracy of airside calculations, and level of detail and options offered. The proprietary nature of the algorithms used by the software was a point of concern for four practitioners, but others specifically stated that the documentation was clear and transparent. On this point, it is likely to be personal preference (i.e., to what degree do practitioners want to access the software code and make changes) and not necessarily a question of accuracy of methodology and coding.

Four practitioners reported using EnergyPlus to simulate natural ventilation. Three others cited the lack of an accessible interface and extensive run times as reasons why they did not use it in their work. For those that did, these same issues seemed to be barriers as well, leading them to generally use it only for limited, initial, low-detail studies of one or two zones. One practitioner who used EnergyPlus more extensively described its use for a renovated university building in the Pacific Northwest. In this project, thermal comfort was a significant goal of the natural ventilation scheme, and the model demonstrated that natural ventilation would be able to maintain thermal comfort in the space. After the building was occupied, his team found that the simulation tool was, in fact, overestimating the temperatures in the space when in NV mode, and they concluded that interior thermal mass (e.g., of less-massive objects such as furniture) was playing a larger role than the model accounted for. Overall, practitioners reported high confidence in EnergyPlus' research-grade abilities and quality of results, but that on most projects, these were outweighed by time and budget constraints.

Other bulk airflow-capable tools reported by practitioners included CONTAM, TRNSYS, and Tas. Two practitioners referenced CONTAM, stating that it was a good numeric tool. For a southern California dormitory, a post-construction study found that CONTAM accurately predicted the very high airflow rates possible (60 ACH) in the space. One practitioner cited TRNSYS' ability to accept custom code as a specific benefit. The use of Tas was reported by two practitioners, who cited it as a good bulk airflow modeling tool that allowed for detailed control of apertures and a versatile results viewer. The lack of ability to do parametric runs or access the input or results as text files for scripting purposes were cited as two main limitations of the software.

CFD tools

CFD was cited by eleven practitioners as being used in some way during their natural ventilation and mixed mode simulation work. In total, practitioners listed ten different CFD software tools that they currently used or had used in the past, including: ANSYS CFX, ANSYS Fluent, Autodesk Simulation CFD (formerly CFDesign), Autodesk Vasari, FloVENT, Flowdesigner, the IES VE Microflo module, PHOENICS, Star-CD, and STAR-CCM+.

CFD was most often used to investigate details of the design (e.g., sizing and locating openings), identify dead spots and conditions under extreme cases, investigate thermal comfort and areas of potential discomfort due to draft risk, and to verify the design in later design stages. The practitioners we interviewed also used CFD to model innovative or atypical NV schemes. For the California Academy of Sciences, CFD was used to allow the project to claim an exemption to the Title 24 requirement that occupants be within 20 feet of an operable window to consider the space properly naturally ventilated. A CFD model of the project showed that a much greater distance between the openings and occupied area would still satisfy the ventilation need. CFD was also successfully used to model a passive downdraft system in a higher education building in California. Post-construction monitoring verified that the flow rates and temperatures predicted by the model were accurate.

As expected, CFD was indeed highly regarded by most practitioners as comprehensive and accurate. Limitations cited had more to do with the user-software interface and included the lengthy run times of CFD models, steep learning curves of the software, and quality of technical support from software developers.

Other tools

eQUEST was mentioned by almost all U.S.-based practitioners as the software of choice for their whole building energy models. Although eQUEST has a built-in natural ventilation function, it is only available for one system type, so practitioners reported using other tools in conjunction with results from eQUEST to evaluate the potential for natural ventilation. Three practitioners reported exporting hourly indoor zone temperatures from eQUEST and comparing them with outdoor temperatures to determine when cooling needs could be satisfied through natural ventilation as an early step in the design process.

Many practitioners reported using in-house tools and spreadsheets to investigate the potential for natural ventilation in their projects. Practitioners at the larger multinational firms we spoke with referenced more advanced in-house tools developed by their firm to do initial thermal and air-side analyses on single or limited zone models. Practitioners at smaller firms reported creating simpler excel-based spreadsheets to post-process results from their simulation tools and to investigate details of buoyancy-driven flow to determine the annual number of hours natural ventilation would be possible. These practitioners stated that this extra step of post-processing outside of conventional simulation tools was necessary, but not optimal.

6.4 Findings: Sources for key inputs

In addition to how practitioners used tools, they were also asked about their sources for common inputs such as boundary conditions, wind and weather data, and occupant-controlled window opening schedules. Practitioners reported a wide range of sources for boundary conditions and wind pressure coefficients for CFD and bulk airflow analyses, including program defaults, assumptions based on climate and building type, thermal models, and standard tables in the ASHRAE handbook.

Most practitioners reported using typical weather files when conducting their analyses (e.g. TMY for the U.S. and CWEC for Canada). Seven practitioners reported that they design their natural ventilation systems to operate under still conditions only and disregard wind speed and direction. Five reported that they would only run an analysis with wind to check for flow reversal, areas of discomfort, or unexpected issues, such as pressure changes. Three stated that they have used site-specific data in the past when it was available. One respondent stated that considering site-specific wind patterns was not necessary because they designed their buildings to work under all wind conditions.

Schedules describing when windows would be open or closed are often a critical influence in modeling natural ventilation systems, but there was no consensus on the approach. Eleven practitioners stated that they used schedules based on an ideal user, assuming that windows would be opened when indoor temperatures were above the comfort range (in the cooling season). Four of these practitioners reported that this was because their systems were always automated, for security, comfort, or ventilation reasons. Of the remaining seven who modeled manually-operated windows, two reported scaling the open area based on indoor temperature.

In addition, two practitioners stated that they applied a probability distribution to their ideal user schedule to account for variations in actual use, while others expressed interest in applying stochastic modeling principles to their schedules in the future. Lastly, three practitioners reported running multiple schedules based on different user types (“worst case” to “best case”) to understand the implications on thermal comfort if the windows were operated in a non-ideal manner.

6.5 Findings: Future direction

Looking forward, practitioners reported what types of improvements and capabilities they would like to see in their simulation tools. While there was no overwhelming consensus as to the preferred direction of tool development, several important suggestions were most prominent.

Integrated tool or data entry interface
Practitioners stated that it would be more helpful to have a NV and MM tool that was better integrated with the whole building modeling tool, but the details of how this might be achieved differed. Half stated they wanted a combined tool, while half stated that a modular tool with a common geometry input interface would suffice. Most importantly, practitioners stated that they wanted to reduce the time and chance for errors created by repetitively entering the same information into multiple simulation tools.

Improved result visualizations
Practitioners also reported that they wanted to be able to better convey their results to architects and clients, but their preferred methods varied. Some wanted the tool to be able to generate better visualizations depicting accurate airflow paths through the space, and annual time and temperature distributions. Others wanted a tool to provide text-based results that could be imported into their own spreadsheets for script-based graphical post-processing.

Early phase design tools
Lastly, practitioners reported that quick tools meant for early design testing would be valuable in the design process. They stated that many existing tools were designed for compliance or performance modeling and were more difficult to use as iterative design. One practitioner cited CBE's UFAD Cooling Load Design Tool as potential inspiration for a future early design tool for natural ventilation. Such a tool could help designers figure out whether natural ventilation was a viable option for their building based on basic layout and local climate data, and if so, which type of natural ventilation scheme might be best suited for their project.

7. RECOMMENDATIONS FOR FURTHER WORK

Based on the varied responses and stories from all the interview data, and the areas where practitioners found difficulties or differences in model vs. reality, we have compiled a list of what we feel are potentially important areas for further development or research, in addition to those reported by practitioners.

Advanced control sequencing
Multiple practitioners mentioned the inability to model complex controls of more advanced systems (e.g. passive downdraft towers) or mixed mode as a limitation of the software they used. Practitioners stated that they worked around this by manually post-processing the results of their simulations. Allowing for more advanced control sequencing could help practitioners more accurately model their natural ventilation and mixed mode systems, and reduce time spent in post-processing.

Tools to simplify compliance documentation
Practitioners reported difficulties demonstrating energy savings achieved through natural ventilation to the degree required by compliance programs such as LEED. Multiple practitioners said that it was often not worth the effort required to prove that their natural ventilation or mixed mode system would save energy. Adding the ability for simulation tools generate results specifically for compliance documentation could help practitioners streamline the compliance process.

Peer sharing
We received almost unanimous agreement from practitioners that knowing what their peers are doing would be helpful to them. Currently, the largest known database of mixed mode projects can be found on the CBE Mixed Mode website, which provides multiple case studies and a searchable database of over 150 mixed mode projects. While outside the scope of this project, it might be an interesting and useful exercise to gather this and additional mixed mode and naturally-ventilated case study information and organize the projects on a map to allow designers to see projects and systems by climate and geographic region.

8. APPENDICES

A. Initial survey of tools

MM Industry Advisors - Modeling Software Survey

Name

Based on your sense of the overall industry (not just your own work), please indicate how often you think each software is used (alone or in combination with other programs) to model naturally ventilation and/or mixed mode bulidings

	Never	Rarely	Sometimes	Often	Not familiar
Ansys CFX	○	○	○	○	○
BACH (Building Air Change)	○	○	○	○	○
COMIS	○	○	○	○	○
CONTAMW	○	○	○	○	○
DeST (Designer's Simulation Toolkit)	○	○	○	○	○
EnergyPlus	○	○	○	○	○
EnergyPro	○	○	○	○	○
eQuest	○	○	○	○	○
ESP-r	○	○	○	○	○
Fluent	○	○	○	○	○
GenOpt	○	○	○	○	○
IDA Indoor Climate and Energy	○	○	○	○	○
IES Virtual Environment	○	○	○	○	○
Modelica	○	○	○	○	○
PHOENICS	○	○	○	○	○
SUNREL	○	○	○	○	○
TAS	○	○	○	○	○
TRNSFLOW	○	○	○	○	○
TRNSYS	○	○	○	○	○
UrbaWind	○	○	○	○	○

Please list any programs that are missing from the list.

Please leave any comments you have for us here.

Submit

Never submit passwords through Google Forms.

B. Interview Questions

General Questions

1. Geographically, where are your NV and MM projects located?

2. What types of buildings have you simulated NV and MM systems in?

3. When do you conduct NV and MM simulations? What do you hope to learn at the different stages of design?

4. How do you use the results of your simulations? What design changes are being made as a result of your simulation work?

Tool Selection Process

1. What simulation and modeling tools do you use? What tools do you use during different phases of design? How did you select these tools?

In-house Spreadsheets

1. Why did you decide to create your own tools to model NV/MM?

2. What do you use as the basis? Are you using existing guidelines/rules of thumb, for example?

3. What are its inputs, assumptions?

4. How do you incorporate weather data into your tool?

5. What about wind data or occupant behavior?

6. What kinds of output are possible?

7. During what phases of design do you use your tool in your work and how is it useful to you?

8. How have you improved your tool over time?

Tool-specific Questions

1. Analysis method: how do you use this tool?

    a. EnergyPlus-specific: ZoneVentilation Objects

        - Which specific object do you use? (DesignFlowRate, WindandStackOpenArea)

        - Where do you get the inputs for the objects from (flow rates)? E.g. CFD, standard values (ASHRAE tables)

    b. Airflow Network Modeling (EnergyPlus or other)

        - Where do you get your wind pressure coefficients?

- When defining zones, surfaces and openings, how much detail do you use? Where do you get this information (e.g. leakage areas, discharge coefficients for windows, etc.)?

c. CFD tool-specific

- Do you use this tool in conjunction with other tools?

2. Results: why did you select this tool? What results does it provide and how do you use them?

3. Inputs: Where do you get these values from? What level of detail do you need for these?

a. Weather Data: are you doing anything to capture the site-specific weather?

b. Wind Data: Do you account for wind-driven NV?

c. Occupant Behavior: Specifically window-opening behavior, how to model/account for it?

d. Other inputs

- CFD: where do you get information for your boundary conditions? E.g. do you use a typical wind speed and assume continuous wind pressure
- EnergyPlus: How do you import geometry?

General Tool Questions

1. What is most useful about this tool?
2. What are its strengths?
3. What are its limitations?
4. What capabilities do you wish this tool had? How could it be improved? If you could talk to the tool developers directly, what would you recommend?

Follow-up Questions

1. Can you tell me about your most successful NV or MM project and how the simulation work you did contributed?
2. Have you had any big surprises come up on a project regarding NV or MM?
3. Given that we are talking to other practitioners in the industry, what would you hope to get out of the results of our project?
4. How has the simulation of NV/MM changed over your career?
5. Can you recommend anyone else that we should talk to?

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