

Using Coupled Energy, Airflow and IAQ Software (TRNSYS/CONTAM) to Evaluate Building Ventilation Strategies

W. Stuart. Dols
Steven J. Emmerich
Brian J. Polidoro

Engineering Laboratory, National Institute of Standards and Technology
100 Bureau Drive Gaithersburg, MD 20899

Submitted to and published by:
Building Services Engineering Research & Technology
<http://dx.doi.org/10.1177/0143624415619464>

U.S. Department of Commerce
Penny Pritzker, Secretary of Commerce



National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Abstract

Building energy analysis tools are available in many forms that provide the ability to address a broad spectrum of energy-related issues in various combinations. Often these tools operate in isolation from one another, making it difficult to evaluate the interactions between related phenomena and interacting systems, forcing oversimplified assumptions to be made about various phenomena that could otherwise be addressed directly with another tool. One example of such interdependence is the interaction between heat transfer, inter-zone airflow and indoor contaminant transport. In order to better address these interdependencies, the National Institute of Standards and Technology (NIST) has developed an updated version of the multi-zone airflow and contaminant transport modelling tool, CONTAM, along with a set of utilities to enable coupling of the full CONTAM model with the TRNSYS simulation tool in a more seamless manner and with additional capabilities that were previously not available. This paper provides an overview of these new capabilities and applies them to simulating a medium-size office building. These simulations address the interaction between whole-building energy, airflow and contaminant transport in evaluating various ventilation strategies including natural and demand-controlled ventilation.

Practical Application

CONTAM has been in practical use for many years allowing building designers, as well as IAQ and ventilation system analysts, to simulate the complex interactions between building physical layout and HVAC system configuration in determining building airflow and contaminant transport. It has been widely used to design and analyse smoke management systems and evaluate building performance in response to chemical, biological and radiological events. While CONTAM has been used to address design and performance of buildings implementing energy conserving ventilation systems, e.g., natural and hybrid, this new coupled simulation capability will enable users to apply the tool to couple CONTAM with existing energy analysis software to address the interaction between indoor air quality considerations and energy conservation measures in building design and analysis. This paper presents two practical case studies using the coupled modelling tool to evaluate IAQ performance of a CO₂-based demand-controlled ventilation system under different levels of building envelope airtightness and the design and analysis of a natural ventilation system.

Keywords airflow modelling, CONTAM, contaminant transport, coupled models, energy modelling, multizone modelling, TRNSYS

Introduction

Design and analysis of building systems involves a wide range of disciplines and tools to address the many aspects of building performance including energy use, indoor air quality (IAQ), lighting, etc. NIST develops and applies simulation tools that address IAQ and ventilation of the built environment and the interaction between these and other building characteristics, e.g., energy use. Recently, NIST has enhanced existing tools and developed new tools to address the interaction between building airflow, heat transfer and contaminant transport. In some cases, these development efforts provide integration between existing tools to address a general category of phenomenological interaction, e.g., airflow and heat transfer. In other cases, the new tools address a specific design problem, e.g., natural ventilation. The following is a list of recent developments, with details of each provided below along with brief presentations of applications to the design and analysis of buildings and their ventilation systems.

CONTAM (modified)

Allows external control by and exchange of data with other software and provides for scaled, rectilinear drawing of building floor plans.

CONTAM3DExport (new tool)

Extrudes CONTAM project files to three dimensions and creates *TRNSYS3d* and *EnergyPlus* compatible IDF format files.

Type 98 (new tool)

Provides coupling between CONTAM and TRNSYS calculations.

Type56-98Coupler (new tool)

Provides for seamless data exchange between TRNSYS Type 56 and Type 98 during the project definition phase.

Climate Suitability Tool (modified)

Incorporates adaptive thermal comfort analysis when evaluating the climate of a building site for potential implementation of natural ventilation at the preliminary design stage.

LoopDA (modified)

Provides calculations for sizing airflow openings for natural ventilation systems in the design phase.

Building Simulation Software Tools

The first four tools listed above were modified or developed to address the dynamic interaction between heat transfer, airflow and contaminant transport. The last two tools were developed to enable designers to better address natural ventilation during the building design process. However, the enhanced coupling capabilities provided by the first four tools also provide for the analysis of natural ventilation systems in a manner that greatly improves upon existing capabilities.

Improved Heat Transfer, Airflow and Contaminant Transport Coupling

NIST develops and maintains the CONTAM whole-building, multizone airflow and contaminant transport simulation tool [1-3]. CONTAM accounts for the interaction between external driving forces (ambient temperature and wind) and internal mechanisms (building ventilation system airflows) to determine resultant pressures and airflows across internal and external building partitions. It then accounts for external and internal contaminant sources and removal mechanisms to calculate

contaminant transport associated with the previously determined airflows. However, CONTAM relies on user-defined values for internal temperatures. As such, it is better suited for the analysis of mechanically conditioned systems wherein the assumptions of known temperature set-points being met are more reasonable. In order to address this limitation, a form of CONTAM has previously been integrated with the **TRaNsient SYstems Simulation** (TRNSYS) [4] tool, which can perform whole-building multizone heat transfer calculations but requires the input of infiltration and inter-zone airflow rates.

TRNSYS has a modular structure that enables multiple energy-related systems to be considered together within a single simulation environment. Modules are referred to as Types. TRNSYS includes many Types and allows users to develop custom Types for their purposes. TRNSYS Version 17 includes two types that allow for the simulation of multizone building heat transfer and airflow, Type 56 and Type 97, respectively [5]. Type 97 is based on a subset of capabilities of CONTAM including: modeling inter-zone airflows based on a limited number of the mathematical airflow elements available in the current version of CONTAM, and modeling ventilation systems using CONTAM's simple air handling system. This coupling was done in a manner referred to as the *dynamic* coupling approach [6], whereby iteration occurs between the modules within each time step until convergence is obtained and then the simulation proceeds to the next time step. There are several limitations to the current coupling method via Type 97 including:

- no contaminant transport modeling,
- does not utilize CONTAM's full duct model,
- connections with Type 56 are not formed automatically , and
- does not “evolve” with new versions of CONTAM as it is continuously enhanced.

NIST has addressed these limitations by developing a method and a new TRNSYS Type 98 to more fully couple the simulation engine of CONTAM (referred to as *ContamX*) with TRNSYS. The overall approach between the heat transfer and airflow calculations is accomplished via the *quasi-dynamic* method as opposed to the dynamic method. The quasi-dynamic method also referred to as loose coupling [6-8], refers to the coupling between simultaneously running simulation processes, e.g., airflow and heat transfer calculations, whereby data is exchanged only once within each time step, and convergence only occurs within each process, i.e., not between the processes. The quasi-dynamic method was implemented in order to utilize the CONTAM solver in its current form, i.e., without modification to the time stepping algorithm that would be needed to enable inter-process convergence like that implemented between Type 56 and Type 97.

Dols et al. (2015) presents background on the dynamic and quasi-dynamic coupling approaches that have been implemented by various developers in the past. Both methods are capable of addressing the coupled problem, but there are potential numerical issues associated with each method including instabilities and convergence issues related to the numerical methods, simulation parameters and physical behaviors being modeled. Generally, the quasi-dynamic method requires shorter time steps to prevent stability issues. These instabilities arise when utilizing explicit solution techniques to which this coupling method is related, due to the sequential nature of the execution of the separate programs and the lagging in time of the exchange state variables between programs during co-simulation. These convergence and stability issues are presented in citations provided within Dols et al. (2015) including potential numerical reasons [10, 11] and situations in which these issues may arise [12-14].

In order to improve coordination of the exchange of data between Type 56 and Type 98, NIST modified the CONTAM graphical user interface to enable scaled drawing of building floor plans (within the rectilinear confines of the program), and developed the *CONTAM3DExport* tool to “extrude” two-dimensional CONTAM sketches into a three-dimensional file (IDF file) that can be imported into *Trnsys3d* [15]. Another utility, the *Type56-98Coupler*, aids in generating the associated *proforma* that defines the inputs and outputs of Type 98 and in forming the links between the inputs and outputs of Type 56. This process is depicted schematically in Figure 1. Note that *CONTAM3DExport* can also export IDF files that are compatible with *EnergyPlus*.

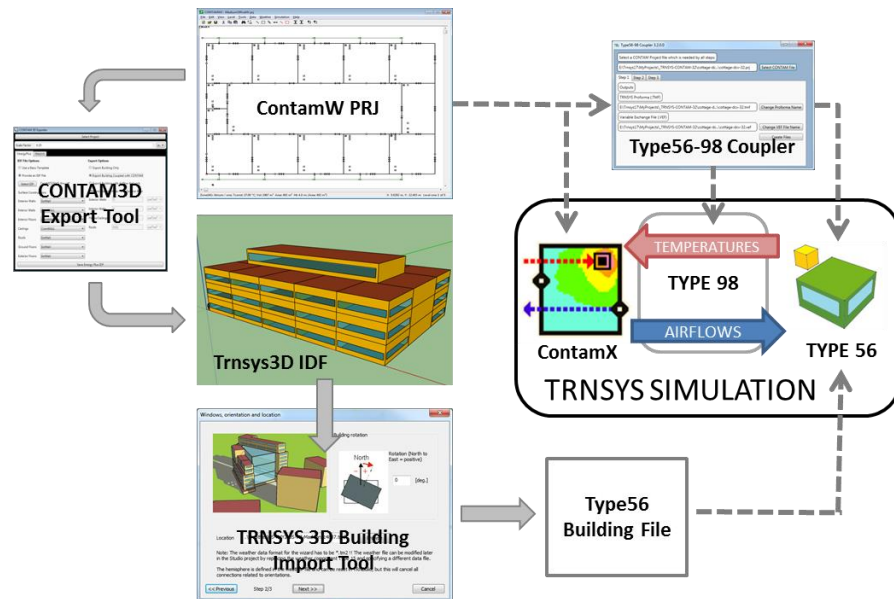


Figure 1 - Schematic depicting coordination between input files and simulation components

Verification testing was performed on the coupled simulation by comparing simulation results with an analytical solution for a single zone model with stack-driven airflow [9]. This verification procedure indicated the airflow and temperature data exchange is taking place properly. Verification and validation of the individual tools themselves have been performed over the course of their existence [16-18].

Demonstration Case #1: Constant Air Volume (CAV) with CO₂-based Demand Controlled Ventilation (DCV)

The first demonstration case provides an overview of the coupling process and capabilities based upon the *Medium Office Building* of the U.S. Department of Energy commercial reference building models [19] that have also been developed as CONTAM models [20]. A scale model of the building was drawn in CONTAM, extruded to a *Trnsys3d* IDF file and then imported/coupled into the TRNSYS Simulation Studio to create a TRNSYS project file using the *Type56-98Coupler*. This process is detailed in the CONTAM documentation [1]. The model is shown as it appears in the graphical interface of CONTAM (referred to as *ContamW*) and *Trnsys3d* in Figure 2.

Case Description. The building consists of three stories, each having a plenum above the occupied space. Each floor consists of open office space, and there is one air handler per floor. The CONTAM model is slightly modified from the *EnergyPlus* model so that each floor includes a stairwell, elevator and restroom served by a dedicated exhaust system. These three zones are shown in the center of the CONTAM sketch in Figure 2. Their inclusion enables consideration of the impact that these vertical shafts and the exhaust system have on the building pressures, airflows and contaminant transport.

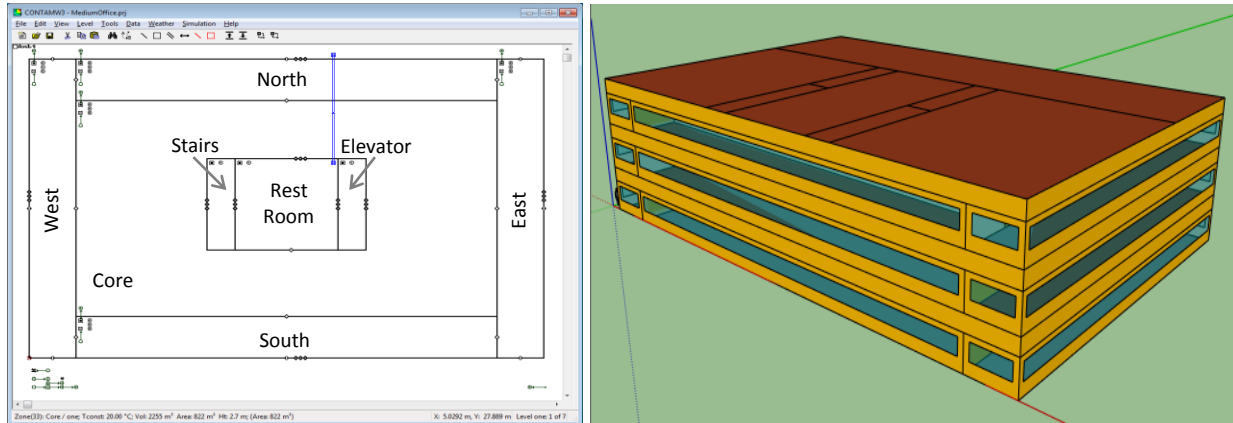


Figure 2 - Medium Office Building model shown in *ContamW* and *Trnsys3d*

The exchange of airflows, temperatures and system controls between the various software components during simulation is outlined in Figure 3. The coupling between *ContamX* and TRNSYS consists of the following data exchange during each simulation time step:

- *ContamX* calculates inter-zone, zone infiltration and air handling system airflow rates
- *ContamX* passes these rates to TRNSYS Type 56 via Type 98
- Type 56 performs the heat transfer calculations to determine air node temperatures
- Type 56 passes air node temperatures back to *ContamX* via Type 98

This data transfer is referred to in Figure 3 as the automatic coupling set up by the *Type56-98Coupler* tool (distinguished in the figure by the red arrows). Other coupling was implemented to simulate the HVAC system with DCV control as follows:

- Sensors in the CONTAM model detect the CO₂ concentrations in the return air plenums of the three floors
- The CONTAM control network adjusts the fraction of outdoor air intake for the associated air handling systems based on sensor values, set-point levels and control logic
- The outdoor air fractions determined by CONTAM are passed to TRNSYS via Type 98 and used to control the outdoor air damper position of the ventilation systems with outdoor air intake (Type 664)
- Type 664 mixes outdoor air and return air and delivers the air to the heating (Type 6) and cooling (Type 92) systems arranged in series
- The outlet air temperature from the heating/cooling system is then used to set the temperatures of the ventilation airflow to the air nodes of the Type 56 building model

TRNSYS provides a diverse set of modules that can be used to develop other systems. The method indicated above is only one example of the many possibilities. There are also many issues that one could study with these coupling capabilities. This case highlights potential impacts of building envelope airtightness on a CO₂ DCV system and resultant effects on contaminant levels associated with indoor contaminant sources.

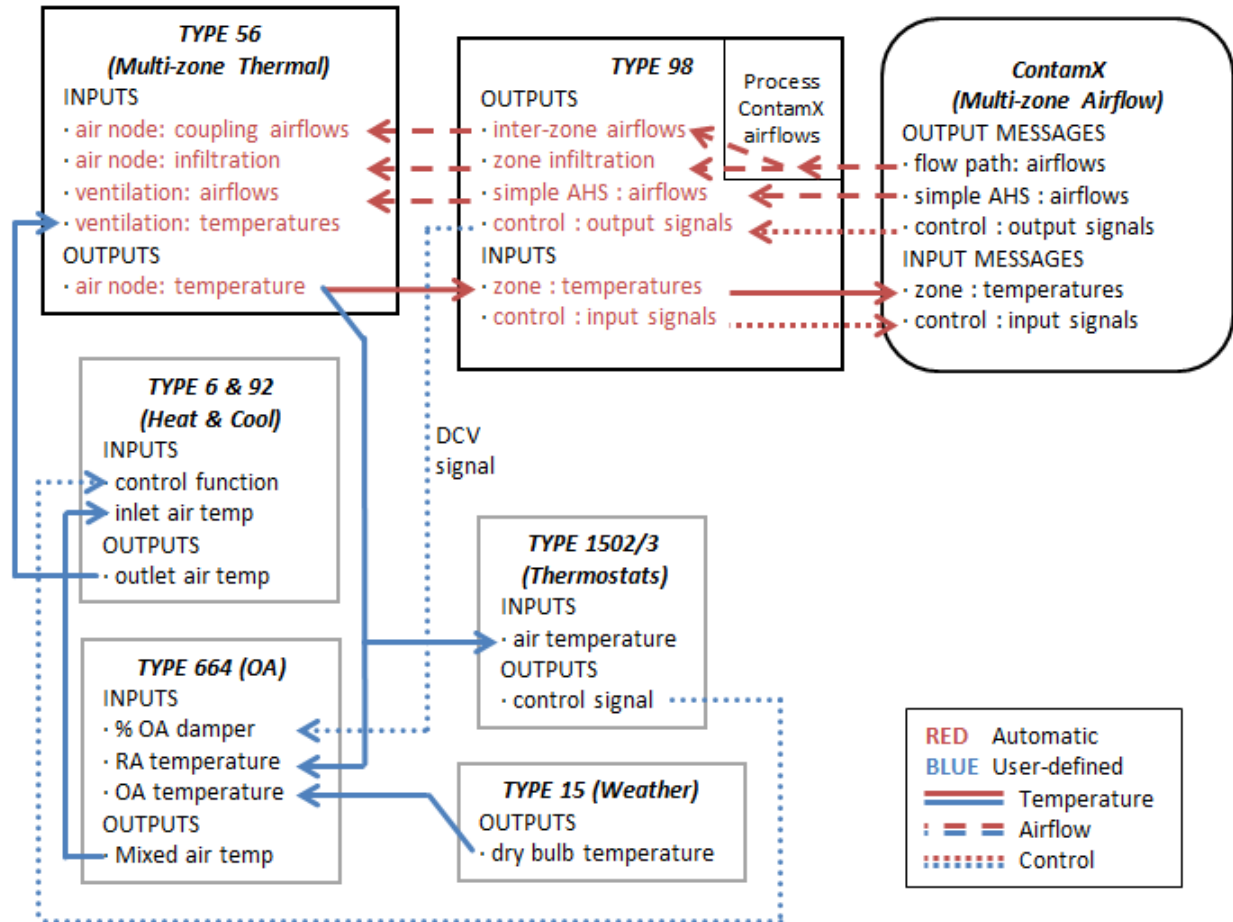


Figure 3 - TRNSYS Type 56/Type 98 input and output coupling diagram for DCV case

Case Results. The CONTAM/TRNSYS coupling between heat transfer and airflow provides the ability to evaluate ventilation system designs with respect to building envelope tightness using CONTAM's pressure-based airflow network calculations as opposed to the oft-used assumed and empirically-determined air change rates [21]. Figure 4 provides plots of the CO₂ concentration in the three return plenums. The plot on the left is for the base configuration with a building leakage area of 5.27 cm²/m² of building envelope surface area and that on the right is for a tighter envelope having a leakage area of 0.527 cm²/m². As shown in Figure 4, there is less variation in the CO₂ concentrations among the three zones in the tighter building. This result highlights an important benefit of doing multizone airflow calculations, which is to fully account for interzone and envelope airflows that result from leakage between interior zones and across the building envelope under specified weather conditions and ventilation system airflow rates.

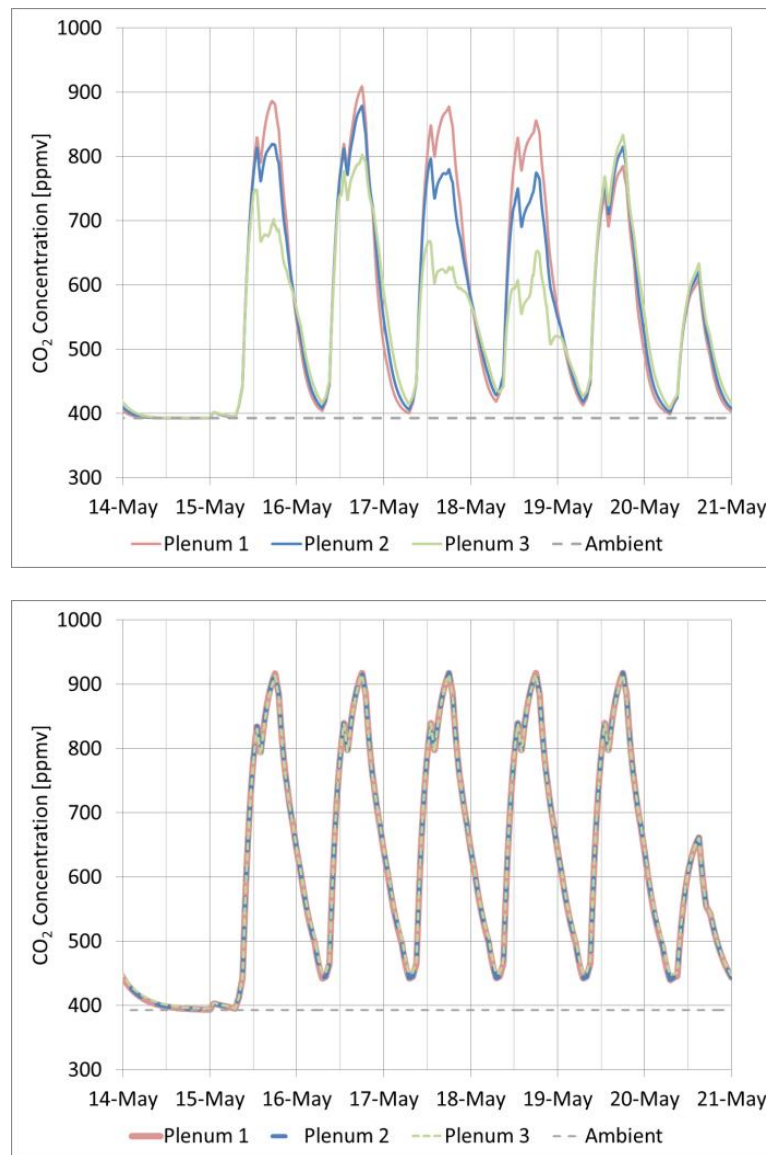


Figure 4 - CO₂ concentration for DCV system in leaky building (Top) and tight building (Bottom)

The coupling of heat transfer, airflow and contaminants enables comparisons to be made between various ventilation systems that utilize contaminant-based control strategies. Not only can users evaluate systems based on the controlled contaminants, e.g., CO₂ in this case, but the effect on non-control based contaminants can be evaluated as well. In order to demonstrate the latter effects, this case includes internal sources of volatile organic compounds (VOCs). Figure 5 shows the building average VOC concentration for four different combinations of building envelope leakage and ventilation system type: leaky envelope with CAV system, tight envelope with CAV system, leaky envelope with CAV-DCV system and tight envelope with CAV-DCV system. This plot reveals that the internal concentration is elevated for the lower outdoor air intake rates associated with the DCV control system for both the leaky and tight envelopes. Further, but not addressed here, the effects on energy usage of these different ventilation strategies can be evaluated using the capabilities that are inherent to TRNSYS, thus enabling evaluation of trade-offs between energy conservation strategies and IAQ.

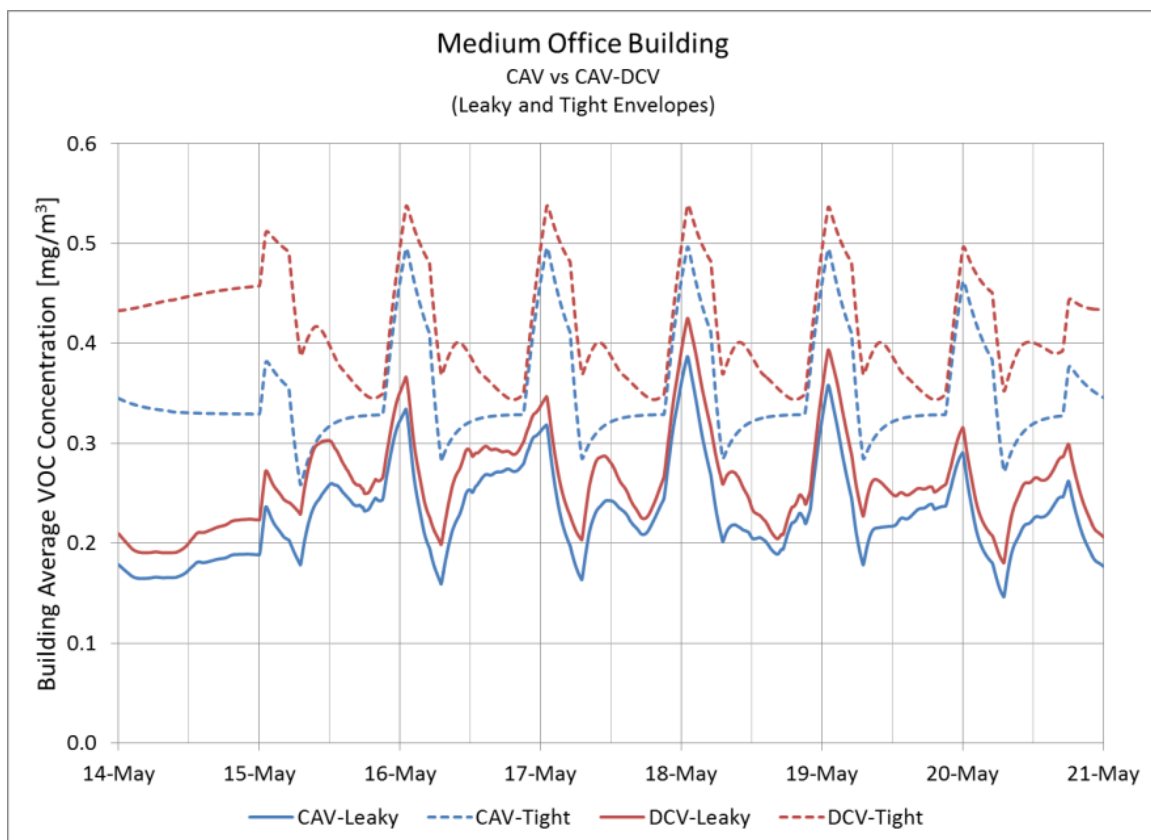


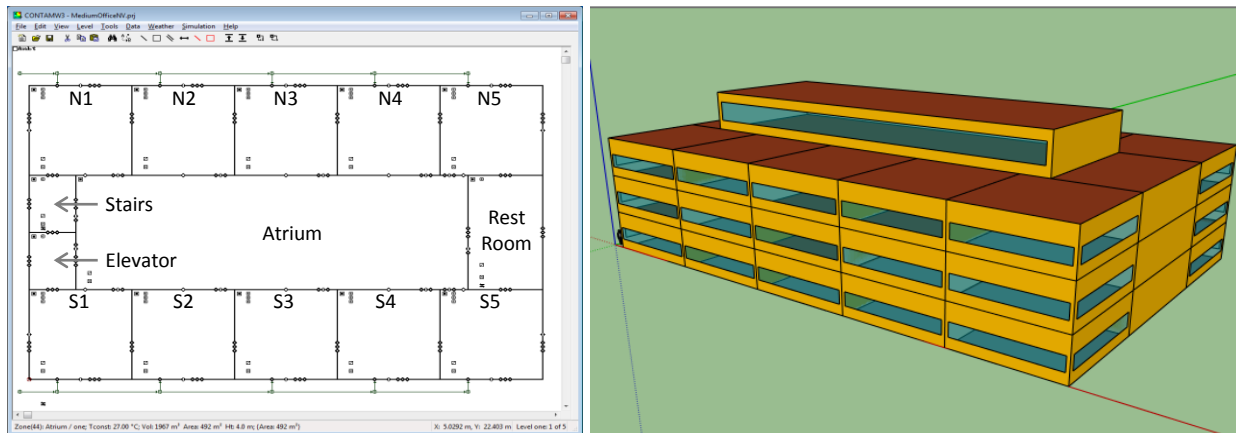
Figure 5 - Comparison of VOC concentrations with respect to envelope leakage and ventilation system

Natural Ventilation Design and Analysis Tools

NIST has also developed two tools to support the design of natural ventilation systems [22-24]. The *Climate Suitability Tool* is used to evaluate the potential of a given location for direct ventilative cooling and nighttime ventilative cooling. The climate suitability analysis is based on a general single-zone thermal model of a building configured to make optimal use of direct and/or nighttime ventilative cooling. The second tool, *LoopDA*, is based on the methodology presented by CIBSE in *Applications Manual AM10: 1997 - Natural Ventilation in Non-domestic Buildings* [25] and more specifically on the work done by Axley [26]. These two tools are intended to be used in the early design phase and the results can then be utilized within the newly coupled TRNSYS/CONTAM model to perform a more complete analysis. This process is outlined in the following demonstration case.

Demonstration Case #2: Natural Ventilation System Design and Analysis

Case Description. For the purposes of the natural ventilation case, the Medium Office Building model was modified as shown in Figure 6. Modifications include the addition of a central atrium with stacks (not shown in the figure) located at the top to provide common outflow paths for natural ventilation flows; removal of the plenum levels; subdivision of each of the north and south sides of the building into five 100 m³ offices; and relocation of the restrooms, elevator and stairs to opposite ends of the building.



**Figure 6 - Medium Office Building model modified for natural ventilation
as shown in *ContamW* and *Trnsys3d***

The TRNSYS/CONTAM simulation setup is much simpler for this case, because there is no need to couple mechanical ventilation systems between the two domains. However, the models could be modified to incorporate hybrid ventilation systems.

Case Results. A climate suitability analysis shown in Figure 7 was performed using TMY3 typical hourly annual climatic data for Baltimore, Maryland USA with the following inputs: adaptive thermal comfort with 80 % acceptability and a 17 °C dew point limit; specific combined internal and solar gains, q_i , of 30 W/m²; and a minimum ventilation rate for office space based on ASHRAE Standard 62.1-2013 [27] of 0.425 L/s-m² or approximately 15 m³/h per office.

The results presented in Figure 7 indicate the direct ventilative cooling potential given by: the average air change rate required based on only those hours when direct cooling is effective, the standard deviation of those air change rates, the percentage of the year direct cooling is effective, i.e., the number of hours direct ventilation is effective out of the total number of hours in the weather file, and the percentage of hours for which the ambient conditions were too cold, too hot, or too humid for natural ventilative cooling. The *Climate Suitability Tool* also provides information on night cooling potential.

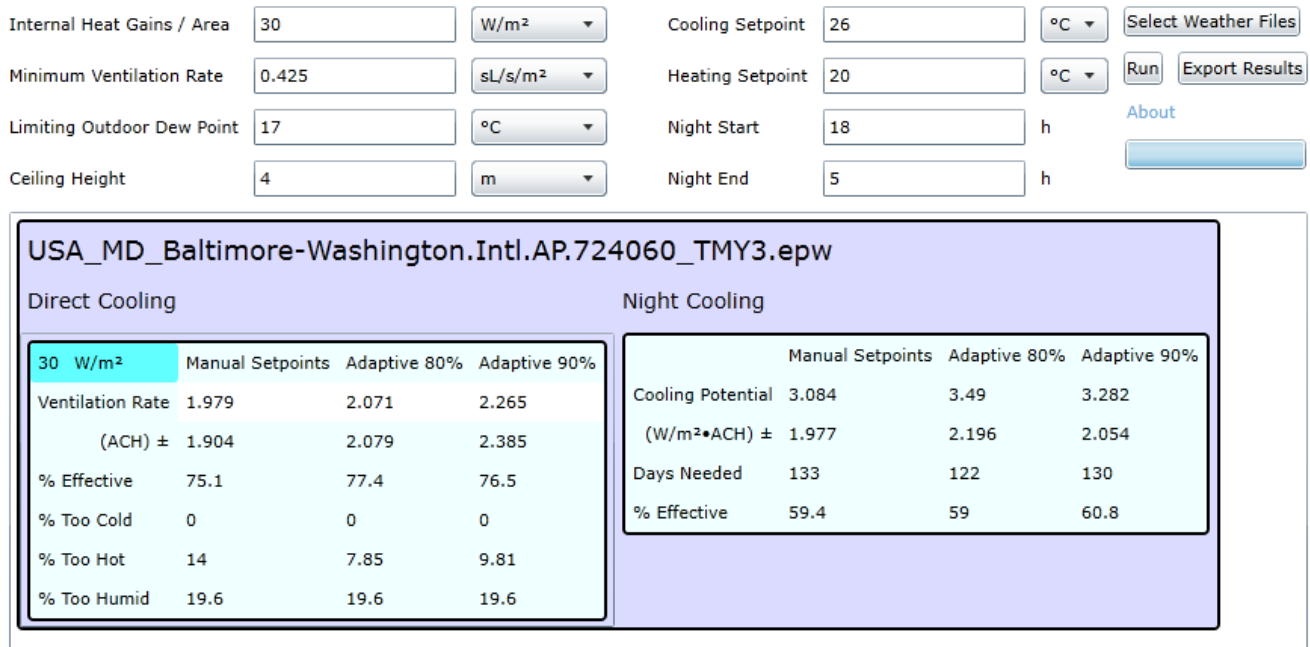


Figure 7 - Climate suitability analysis and results in web-based application

A *LoopDA* model was developed for a single cross-section of the building to include two offices on opposite sides of the building separated by the atrium as shown in Figure 8. The arrows through the building represent the so-called pressure loops established by the user to indicate the desired flow patterns through the building. Design conditions shown in Figure 9 are set by the user and used to determine the size of the natural ventilation openings required to provide the design airflow rates. At these design conditions, airflow rates between 1080 m³/h and 1200 m³/h are required to cool the interior to the indoor design temperature of 27 °C. A set of self-regulating inlet vents (SRV) was defined so that each provides a maximum airflow rate of 70 m³/h, requiring 16 or 17 vents per office to provide the maximum flow rates and two to three vents per office to provide the minimum airflow rate.

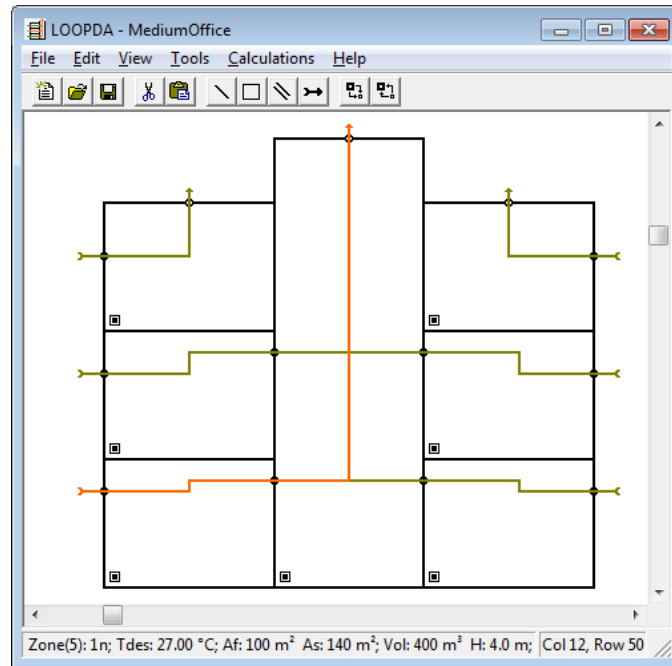


Figure 8 - *LoopDA* representation showing a cross section of the building in elevation view

Figure 9 - *LoopDA* design conditions

During the *LoopDA* analysis, all purposeful inlets, outlets and intermediate flow path sizes were determined, which were then used to develop a CONTAM model of the entire building as shown in Figure 6. The three dimensional extrusion and coupling process to support the coupled TRNSYS/CONTAM analysis was then carried out as described in the previous example.

The fully coupled model provides the ability to evaluate the performance of the natural ventilation system within the context of the entire building, as opposed to the idealized assumptions used during both the climate suitability analysis and the loop design method. An annual simulation can be performed and results analysed to evaluate the design in more detail. Figure 10 presents the annual hourly temperatures of two zones (zone 5 on the north side of level 1, 1-N5 and zone 3 on the north side of level 3, 3-N3). The two dashed lines provide the region of thermal comfort between which the operative temperature should fall based on the monthly average outdoor temperature. While a direct comparison between operative temperature and thermal comfort requirements was not made here, it is apparent that different zones will experience different temperatures and the coupled simulations provide the means to evaluate performance in a detailed manner.

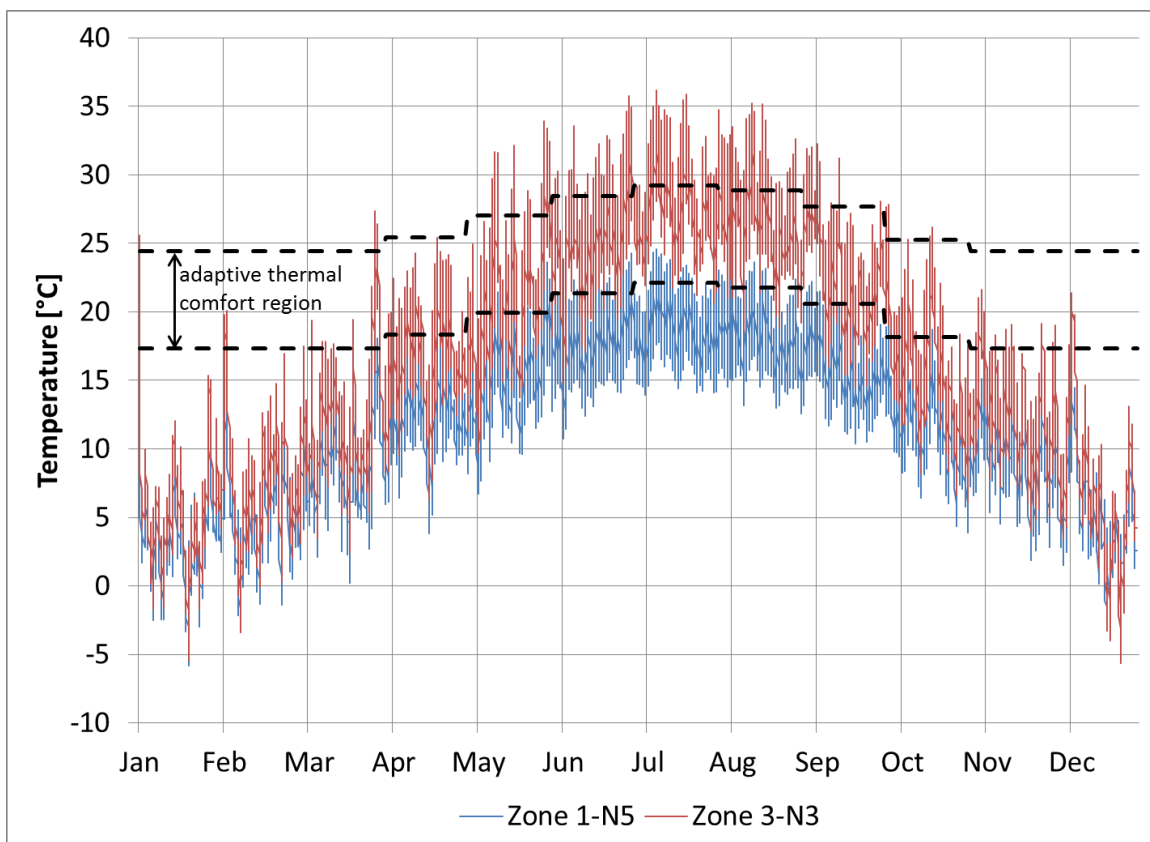


Figure 10 - Temperature of two zones and adaptive thermal comfort region for naturally conditioned spaces and Baltimore weather

The natural ventilation design was performed based on a single set of design conditions. However, it is important to address other conditions under which the system must perform. While there are a wide variety of control schemes that one could employ, this case study simply demonstrates that control can be implemented using a fairly simple scheme. Figure 11 shows airflow rates through the self-regulating

vents of one of the zones (zone 4 on the north side of level 3, SRV_3-N4). In the figure, the solid lines are airflow and the dashed line is the outdoor temperature. Both the controlled and uncontrolled flows are presented.

In the uncontrolled case (SRV_3-N4_uc), the design maximum number of SRVs were left open at all times, and in the controlled case (SRV_3-N4_c), the number of SRVs was controlled based on the outdoor temperature. The ambient temperature was sensed within TRNSYS and an equation type was used to adjust the number of SRVs from the minimum of two when the temperature was at or below the heating balance point (T_{hbp}) up to the maximum number of SRVs (as per the previously presented design information) when the temperature reached the cooling set-point (T_{csp}).

A week in January reveals the difference between the two cases. The uncontrolled airflow rates reached much higher levels and even fell below the required minimum due to the difference in inside-outside temperature and pressure leading to reversed flow through the openings. However, the SRVs were designed to minimize flow reversal. When the control scheme was implemented, the flows were greatly reduced. However, minimum airflow was still not always maintained due to periods when reverse stack pressures were exhibited. This behaviour could further be addressed by other means such as a hybrid ventilation scheme whereby fan assist could be implemented to drive ventilation airflow. CONTAM does provide the ability to simulate such systems.

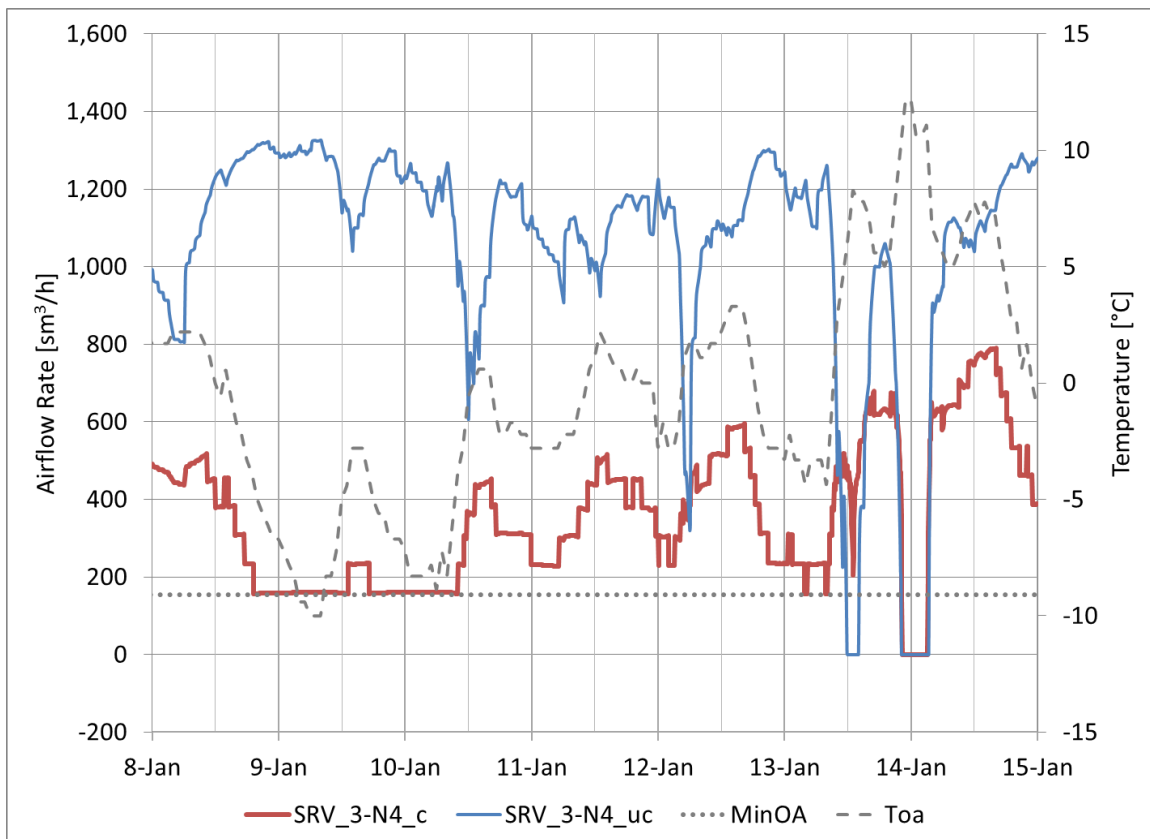


Figure 11 - Comparison between uncontrolled and controlled natural ventilation inlets

Conclusions

The design and analysis of high performance buildings to meet demanding energy and IAQ goals increasingly requires advanced building modeling capabilities to simultaneously model heat transfer, airflow and pollutant transport. An updated multizone building heat transfer, airflow and contaminant transport simulation tool was developed through quasi-dynamic coupling of the TRNSYS energy simulation program with the CONTAM multizone airflow and IAQ model. Along with new supplementary utilities, this coupling capability greatly expands functionality and increases the usability of coupled building energy and airflow simulation by adding multizone contaminant transport and incorporating automatic formation of temperature and airflow connections between the building energy and airflow models. Application of the new coupled tool was demonstrated on a medium office building with CO₂-based DCV and natural ventilation, but many additional design issues of interest can be analyzed with this new approach.

Disclaimer

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

References

1. Dols, W.S. and B.J. Polidoro. 2015. *CONTAM User Guide and Program Documentation*, NIST Technical Note 1887. National Institute of Standards and Technology: Gaithersburg, MD.
2. Dols, W.S. 2001. *NIST Multizone Modeling Website*, NISTIR 6728. National Institute of Standards and Technology: Gaithersburg.
3. Wang, L., W.S. Dols, and Q. Chen. 2010. An Introduction to the CFD Capabilities in CONTAM 3.0, in SimBuild 2010 - Fourth International Conference of IBPSA-USA. IBPSA: New York City, NY.
4. Duffy, M.J., M. Hiller, D.E. Bradley, W. Keilholz, and J.W. Thornton. 2009. TRNSYS - Features and Functionality for Building Simulation 2009 Conference, in 11th International IBPSA Conference - Building Simulation 2009. International Building Performance Simulation Association: Glasgow, United kingdom. p. 1950-1954.
5. McDowell, T.P., S.J. Emmerich, J.B. Thornton, and G.N. Walton. 2003. *Integration of Airflow and Energy Simulation Using CONTAM and TRNSYS*. ASHRAE Transactions, **109**(2): p. 757-770.
6. Zhai, Z.J. and Q.Y. Chen. 2005. *Performance of Coupled Building Energy and CFD Simulations*. Energy and Buildings, **37**(4): p. 333-344.
7. Trcka, M., M. Wetter, and J.L.M. Hensen. 2009. An Implementation of Co-Simulation for Performance Prediction of Innovative Integrated Hvac Systems in Buildings in Building Simulation 2009. International Building Performance Simulation Association: Glasgow, Scotland. p. 724-731.
8. Hensen, J.L.M. 1995. *Modelling Coupled Heat and Airflow: Ping Pong Vs. Onions*, in 16th AIVC Conference. OSCAR FABER PLC: Palm Springs, CA. p. 253-253.
9. Dols, W.S., L. Wang, S.J. Emmerich, and B.J. Polidoro. 2015. Development and Application of An Updated Whole-building Coupled Thermal, Airflow and Contaminant Transport Simulation Program (TRNSYS/CONTAM). Journal of Building Performance Simulation, **8**(5): p. 326-337.
10. Lorenzetti, D.M. 2002. *Computational Aspects of Nodal Multizone Airflow Systems*. Building and Environment, **37**(11): p. 1083-1090.
11. Weber, A., M. Koschenz, V. Dorer, M. Hiller, and S. Holst. 2003. TRNFLOW, A New Tool for The Modelling of Heat, Air And Pollutant Transport in Buildings within TRNSYS, in Eight International IBPSA Conference. IBPSA: Eindhoven, Netherlands.
12. Li, Y. and A. Delsante. 2001. *Natural ventilation induced by combined wind and thermal forces*. Building and Environment, **36**(1): p. 59-71.
13. Li, Y., A. Delsante, Z. Chen, M. Sandberg, A. Andersen, M. Bjerre, and P. Heiselberg. 2001. *Some examples of solution multiplicity in natural ventilation*. Building and Environment, **36**(7): p. 851-858.

14. Axley, J.W., S.J. Emmerich, and G.N. Walton. 2002. Modeling the Performance of A Naturally Ventilated Commercial Building with A Multizone Coupled Thermal/Airflow Simulation Tool. *ASHRAE Transactions*, **108**(2): p. 1260-1275.
15. TRANSOLAR. *Trnsys3d website*. Accessed 2013. Available from: http://trnsys.de/docs/trnsys3d/trnsys3d_uebersicht_en.htm.
16. Kummert, M., D. Bradley, and T.P. McDowell. 2005. Combining Different Validation Techniques for Continuous Software Improvement - Implications in the Development of TRNSYS 16, in eSim 2004. IBPSA: Vancouver, Canada.
17. Emmerich, S.J. 2003. Validation of CONTAMW Predictions for Tracer Gas in a Townhouse., in Building Simulation 2003, 8th International Building Performance Simulation Association (IBPSA) Conference. Proceedings. IBPSA: Eindhoven, Netherlands.
18. Walton, G.N. 1989. *AIRNET - A Computer Program for Building Airflow Network Modeling*, NISTIR 89-4072. National Institute of Standards and Technology: Gaithersburg, MD.
19. Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, and M. Rosenberg. 2011. *US Department of Energy Commercial Reference Building Models of the National Building Stock*, NREL/TP-5500-46861 National Renewable Energy Laboratory: Golden, Colorado.
20. Ng, L.C., A. Musser, A.K. Persily, and S.J. Emmerich. 2012. *Airflow and Indoor Air Quality Models of DOE Reference Commercial Buildings*, NIST Technical Note 1734. National Institute of Standards and Technology: Gaithersburg, MD.
21. Ng, L.C., A.K. Persily, and S.J. Emmerich. 2013. Consideration of Envelope Airtightness in Modelling Commercial Building Energy Consumption, in AIVC Airtightness Workshop. AIVC: Rockville, MD.
22. Emmerich, S.J., W.S. Dols, and J.W. Axley. 2001. *Natural Ventilation Review and Plan for Design and Analysis Tools*, NISTIR 6781. National Institute of Standards and Technology: Gaithersburg, MD.
23. Dols, W.S., S.J. Emmerich, and B.P. Polidoro. 2012. *LoopDA 3.0 - Natural Ventilation Design and Analysis Software User Guide*, NIST Technical Note 1735. National Institute of Standards and Technology: Gaithersburg.
24. Emmerich, S.J., B. Polidoro, and J.W. Axley. 2011. Impact of Adaptive Thermal Comfort on Climatic Suitability of Natural Ventilation in Office Buildings. *Energy and Buildings*, **43**(9): p. 2101-2107.
25. Irving, S. and E. Uys. 1997. *Natural Ventilation in Non-domestic Buildings. Applications Manual AM10*. Chartered Institution of Building Services Engineers (CIBSE): London.
26. Axley, J.W. 2001. *Residential Passive Ventilation Systems: Evaluation and Design*, AIVC Technical Note 54. International Energy Agency: Coventry, Great Britain.
27. ANSI/ASHRAE. Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality. ASHRAE: Atlanta.