Cross-platform, Public Domain Simulation Tools for Performing Parametric IAQ and Energy Analysis

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ABSTRACT

As building design is being driven towards lower energy use, the relationship between indoor air quality (IAQ) and energy becomes more important due in large part to reduced building envelope leakage, which can lead to higher indoor pollutant levels. Simulation tools that can analyze building design measures that aim to improve IAQ and energy use are necessary for evaluating potential trade-offs involving such measures. This paper will present the use of CONTAM and EnergyPlus, coupled using co-simulation, to perform parametric analysis of IAQ and energy impacts. Both of these tools are available in the public domain and provide cross-platform methods to evaluate both IAQ and energy use. Applications and workflow using these tools and available building models will be presented, including various energy and IAQ related measures that can be addressed with them. In particular, we present a framework for addressing energy measures (envelope tightening, insulation, and mechanical ventilation) and IAQ-related parameters (indoor/outdoor sources, ventilation rate, and filtration) in multi-family housing and effects on occupant exposure via a cohesive simulation environment that minimizes inter-domain coupling issues.

KEYWORDS

CONTAM, co-simulation, energy, EnergyPlus, indoor air quality, whole building simulation

INTRODUCTION

Building energy and indoor air quality (IAQ) are intertwined due to the interdependence of heat transfer, airflow, and contaminant transport. Often the same mechanical systems are utilized to maintain the thermal properties of air, e.g. temperature and relative humidity, and to dilute and/or remove pollutants that exist in the indoor environment, e.g., via outdoor air ventilation and filtration. As such, tools are needed to simulate these transport phenomena and associated systems to enable consideration of the interactions of these domains that are important to the health and comfort of building occupants. These tools will support the design and economic considerations of various stakeholders in the building community, including community planners, standards developers, designers and equipment manufacturers.

As highlighted by Teichman et al. (2015), activities related to design and construction of high-performance buildings (HPB) tend to focus heavily on energy-related concerns, and IAQ is often not addressed in a comprehensive and consistent manner. This is also borne out in the common use of building energy simulation, but not IAQ, in HPB design and analysis. However, recent activities by those evaluating HPBs from an IAQ perspective are bringing to bear building simulation methods that address both the energy and IAQ.

Building simulation is often employed to evaluate the impact of various building properties on building performance metrics (Azimi et al. 2016; Fabian et al. 2016). For example, improving building envelope airtightness can affect energy use, indoor contaminant concentrations, and occupant exposure. The ability to evaluate the myriad building types; heating, ventilating, air-conditioning (HVAC) systems; and climate zones, can provide information to those making decisions related to community-level energy use and contaminant exposure (Levy et al. 2016). To this end, two widely-used, public domain software tools, CONTAM and EnergyPlus, have been coupled to enable more complete evaluations of building performance (Dols et al. 2016). On their own, each tool is limited in its ability to account for transport processes upon which building IAQ, airflow and energy may be dependent.

EnergyPlus is a whole building energy simulation program with multizone heat balance as its underlying calculation method (Crawley et al. 2001). EnergyPlus determines zone thermal loads and the energy used by HVAC systems to meet those loads. It calculates zone air temperatures based on current system and plant capacity, including system airflow rates. Generally, infiltration and interzone airflows are user-specified, i.e., not pressure-dependent as in CONTAM, and are not required to be in balance with system airflow rates. Typically, infiltration is modelled based on correlations associated with rectangular, low-rise residential buildings or may be assumed to be constant, but better methods are available (Ng et al. 2018).

CONTAM predicts airflows, contaminant concentrations, and airborne occupant exposures in multizone representations of whole buildings. In this paper, CONTAM will be used to assess IAQ while estimating infiltration airflows that impact building energy use. The CONTAM mass transport model treats a building as a system of interdependent zones or nodes (e.g., rooms, plenums and duct junctions) that store air and contaminant mass, and airflow paths (e.g., openings, cracks and duct segments) that transport air and contaminants between the nodes. Interzone airflows (including flows between the indoors and outdoors) are determined by calculating the node pressures that satisfy mass balance in each node based on driving forces and boundary conditions that include HVAC system airflows as well as wind and stack pressures exerted on the building envelope. CONTAM does not implement heat transfer calculations, so it requires indoor temperatures as inputs, which are often assumed to be ideally met thermostatic set-points.

The fact that CONTAM, when utilized on its own, requires the user to input zone temperature schedules, makes co-simulation with EnergyPlus an improved analysis approach. This is especially important for those who require analysis of both IAQ and energy related building performance.

METHODS

The National Institute of Standards and Technology (NIST) has been working with the Boston University School of Public Health to utilize co-simulation between CONTAM and EnergyPlus to evaluate the impact of energy retrofit programs in multi-family apartment buildings on energy savings and occupant exposure. Co-simulation is being used to evaluate multiple types of building energy retrofits, contaminant sources, and building ventilation systems.

Building Model Overview

The focus of the work to date has been on a four-story, mid-rise apartment building in Boston, Massachusetts. The Mid-Rise Apartment building model is based on the EnergyPlus representation selected from the set of U.S. Department of Energy (DOE) Commercial Reference Building models developed by the National Renewable Energy Laboratory (NREL) (Deru et al. 2011). NIST developed a corresponding CONTAM representation of this building (Ng et al. 2012) to be compatible with the co-simulation approach outlined in Dols et al. (2016). Both models were modified to include stair and elevator shafts that enable simulation of stack flows that can be particularly important to infiltration, energy use and contaminant transport in multi-story buildings.

The base building model, shown in Figure 1, consists of eight apartments on each floor separated by a central hallway with a stair and elevator shaft located at opposite ends of the hallway. Each apartment is served by a dedicated unitary HVAC system with a direct expansion cooling coil, a natural gas heating coil, and a constant volume supply fan. Each apartment is served by a dedicated exhaust system that is scheduled according to the ventilation system type: infiltration only, balanced outdoor air intake, or continuous exhaust ventilation.

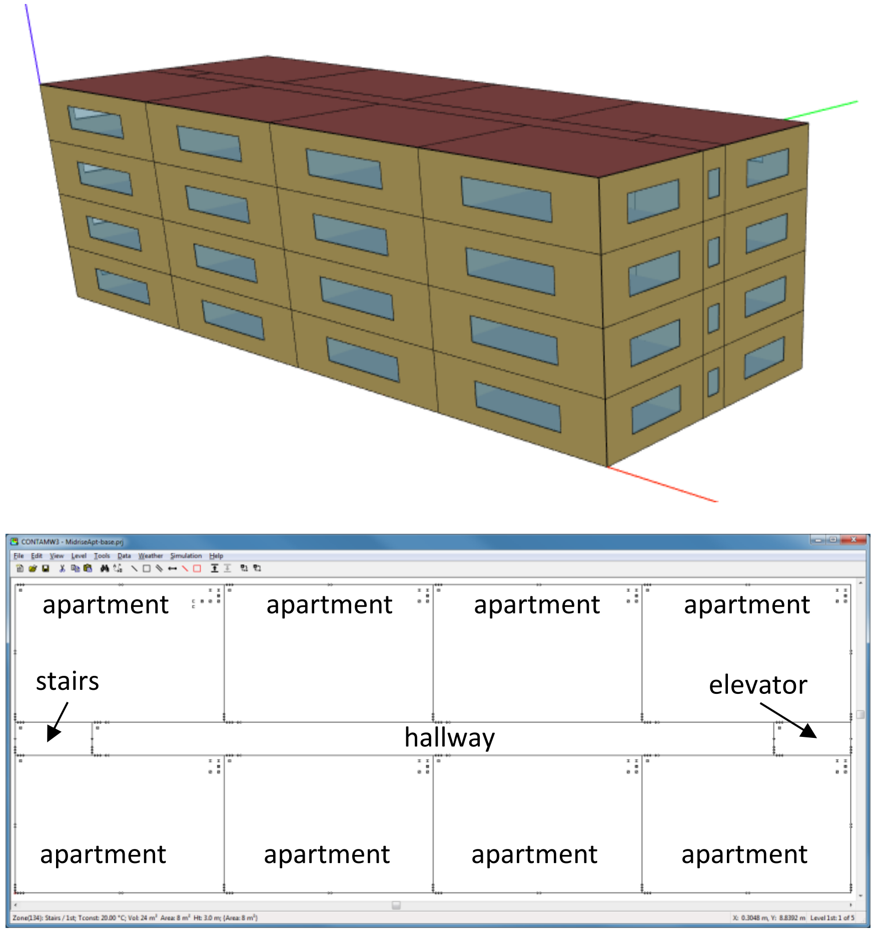


Figure 1. Mid-rise Apartment Building geometry (top) and floor plan in CONTAM (bottom)

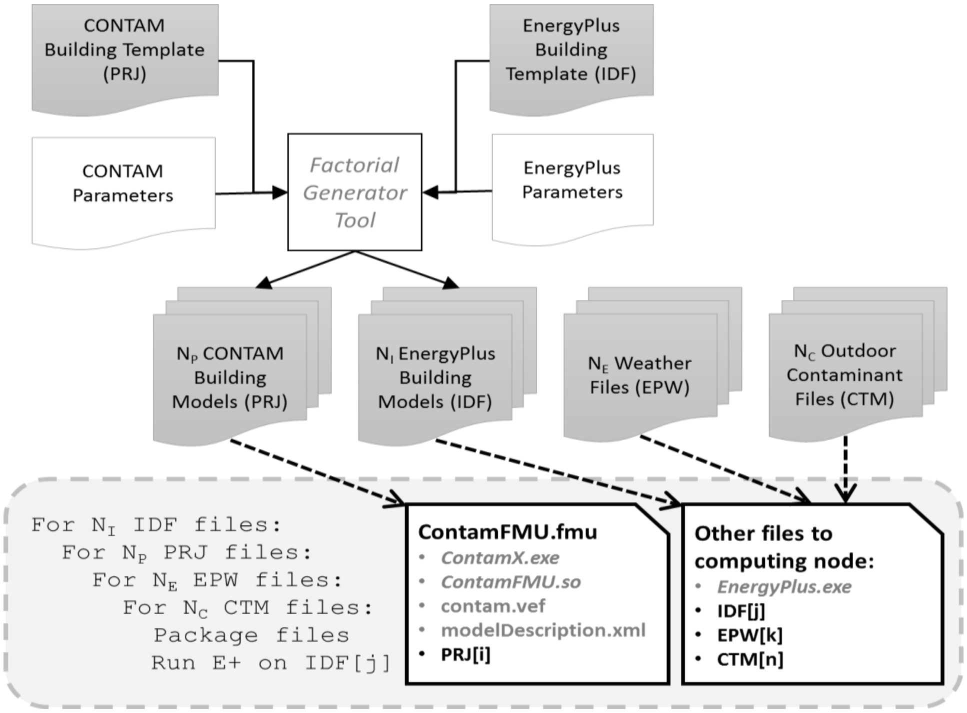
Simulation Tools Development

The EnergyPlus/CONTAM co-simulation capabilities were previously developed as described in Dols et al. (2016). Coupling was implemented based on the Functional Mock-up Interface (FMI) for Co-Simulation specification according to which EnergyPlus was modified to enable the control of coupled simulations (Nouidui et al. 2013). However, the CONTAM co-simulation capability was originally implemented to execute only within the Windows operating system. To run a large set of parametric simulations, we required that the co-simulation capability be ported for execution on a high-performance, Linux cluster maintained by Boston University. EnergyPlus and the CONTAM simulation engine (ContamX) were already Linux compatible, so it was necessary to port the component that facilitates the FMI capability between EnergyPlus and CONTAM referred to as the ContamFMU dynamic link library (DLL). Modifications were made to enable the same source code to be used to build the Windows DLL (ContamFMU.dll) and the Linux equivalent referred to as a *shared object* (ContamFMU.so). Modifications were also required to address the methods used to spawn the ContamX process and enable socket communications to perform within the Linux, multi-core processing environment.

Simulation Setup

The simulation process and associated input files are illustrated in Figure 2. Base building models (template files) were developed for both EnergyPlus (IDF file) and CONTAM (PRJ file). Each of these templates was modified using a text editor to flag relevant values for replacement via a *Factorial Generator Tool* that reads both the flagged input file and a variable parameter file (*PRJ Parameters* and *IDF Parameters*) to create a full set of simulation input files. For the purposes of this demonstration case, Table 1 presents the set of parameters that were varied for a total of 810 simulations. However, these methods can be applied in an almost limitless number of combinations.

The IDF files and PRJ files were generated by the *Factorial Generator Tool* prior to simulation. Scripts were then used to submit jobs to the process manager on the Linux cluster, after packaging files together as required for execution by EnergyPlus using co-simulation. The script then called EnergyPlus and CONTAM post-processing software (ReadVarsESO and simread3, respectively) to glean data from results files for further statistical evaluation.



```
For N_I IDF files:
  For N_P PRJ files:
    For N_E EPW files:
      For N_C CTM files:
        Package files
        Run E+ on IDF[j]
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Figure 2. Schematic of parametric simulation process. N_P, N_I, N_E and N_C indicate number of respective file types: CONTAM building model (PRJ), EnergyPlus building model (IDF), weather (EPW), and outdoor contaminants (CTM).

Table 1. Set of Values for Parametric Simulations

Program	Parameter	Values
EnergyPlus (IDF file)	Ventilation Type	Infiltration only, Balanced supply, Exhaust
	Insulation (Walls/Roof)	R12/R13, R16/R30, R21/R35
CONTAM (PRJ file)	Envelope Leakage Rate (L/s·m^2 @75 Pa, exponent 0.65)	10.19, 5.42, 1.25
	Cooking Source	None, Low Cooking, High Cooking, Low Cooking w/ Local Exhaust, High Cooking w/ Local Exhaust
	Smoking Source	Non-Smoking, Smoking
	Filtration - Minimum Efficiency Reporting Value (MERV)	4, 8, 12

RESULTS

Results presented here are based on simulations performed using Boston, MA weather and outdoor $PM_{2.5}$ data as described in Fabian et al. (2012), i.e., EnergyPlus weather (EPW) and CONTAM contaminant (CTM) files respectively. Detailed analysis of these results will be presented in future publications, but we present a subset of results to demonstrate the capabilities. The first case is a building with indoor particle sources of high-cooking activity and smoking, and outdoor particles, an indoor formaldehyde source, a MERV 4 filter in each air handler, and a relatively leaky building envelope. The second case is the same building with no indoor particle sources, MERV 12 filters, and a relatively tight building envelope. Each case was modelled with three types of ventilation systems: infiltration only, exhaust only, and balanced outdoor air. Figure 3 and Figure 4 present box-whisker data generated by CONTAM and show the average (line inside the boxes), standard deviation, and maximum and minimum air change rates and energy use (Figure 3) and concentrations averaged across all occupied zones (Figure 4).

Figure 3 shows whole-building air change rates and total annual energy use. In terms of energy use, all the buildings have the same insulation levels, so they only differ by envelope leakage and ventilation system type. As shown in Figure 3, the tighter buildings have reduced infiltration rates and lower total energy use for the respective ventilation systems.

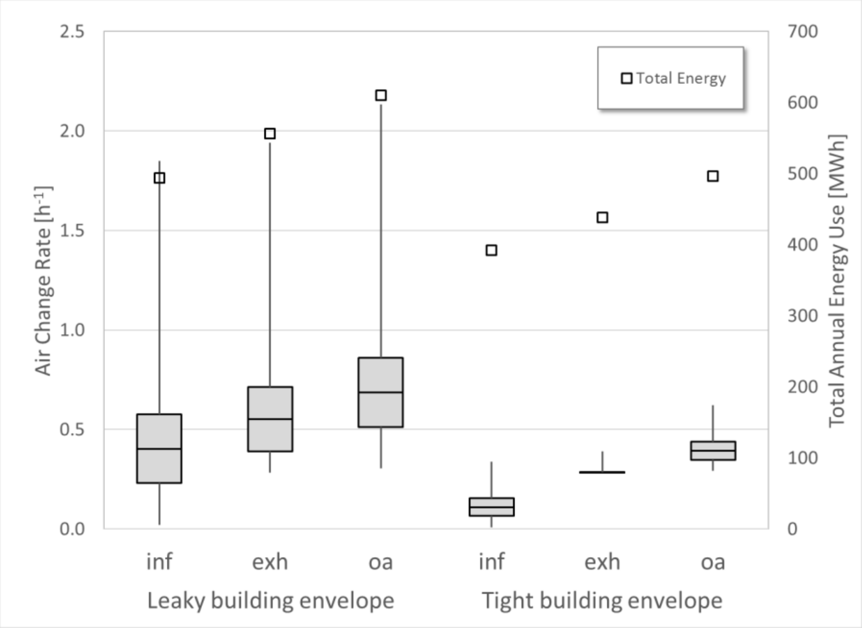

Figure 3. Simulated whole building air change rates and total energy use of a Mid-rise Apartment Building with relatively leaky and tight building envelopes and three different ventilation systems: infiltration only (inf), exhaust only (exh), and balance outdoor air (oa).

Figure 4 shows indoor particle concentrations (grey boxes) and formaldehyde concentrations (yellow boxes). As expected, there are significant differences between indoor particle levels when source control and filtration are implemented. However, the indoor formaldehyde source leads to elevated concentrations in the tighter buildings especially when no mechanical ventilation is provided. Conversely, from the perspective of improving IAQ, increasing dilution by ventilation may reduce contaminant levels of indoor sources but could lead to increased levels of outdoor pollutants and increased energy use. This is demonstrated in the second case, which shows that exhaust only ventilation, when compared to infiltration only, has lower formaldehyde concentrations but slightly higher particle concentrations due to particles being drawn in through the building envelope, along with a higher total annual energy use. These examples highlight the need for an integrated approach to building design and analysis (ASHRAE 2017).

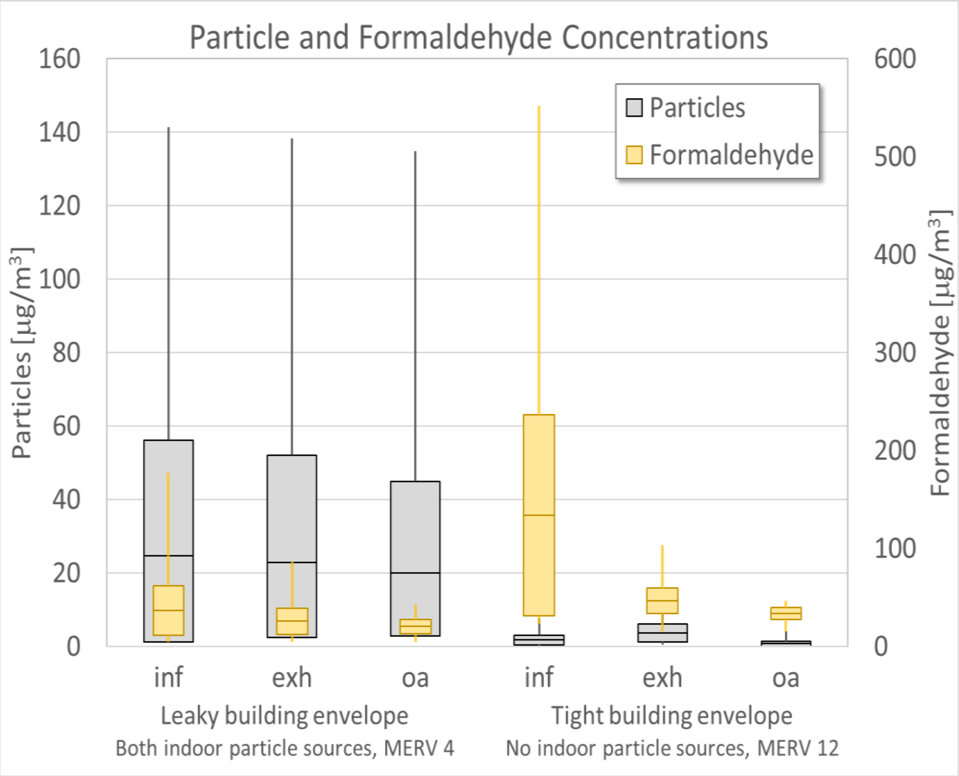

Figure 4. Simulated particle and formaldehyde concentrations averaged over all occupied zones of a Mid-rise Apartment Building for two cases of envelope air-tightness and source emissions scenarios with three different ventilation systems: infiltration only (inf), exhaust only (exh), and balance outdoor air (oa).

CONCLUSIONS

Co-simulation between whole-building IAQ, airflow, and energy simulation programs provides a comprehensive tool to evaluate the interactions between IAQ and energy when considering building energy retrofits. This paper highlighted the development and application of cross-platform, parametric simulation tools that provide the foundation to an integrated approach to building design and analysis to address energy and IAQ. The benefits of this integrated approach were demonstrated with an example from a case study carried out by Boston University and NIST. This example showed the interactions between building energy measures and IAQ parameters and their effects on whole-building energy use and occupant exposures, including reduced energy levels from envelope tightening and occupant exposure commensurate with source location and ventilation.

While these tools and parametric analysis methods are useful in their current state, there is also much work to be done to explore and improve them. For example, the coordination of CONTAM and EnergyPlus models is critical to success, and current methods rely on detailed knowledge of both simulation tools. Tools and associated workflows are available to minimize the redundancy and errors associated with coordinating the building representations, but modifications of existing building models can be quite cumbersome. Therefore, one of the goals of this work is to develop a set of coupled building models to be made publicly available. Output of the simulation tools can be voluminous and difficult to manage. However, they can also provide much greater insight into the interaction among the input parameters and building performance metrics than was presented herein. Work could also be done to provide outputs of desired metrics either directly or by enabling output to be easily manipulated by data processing utilities or scripts.

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REFERENCES

ASHRAE. 2017. ASHRAE Position Document on Indoor Air Quality. edited by Refrigeration American Society of Heating, Air-conditioning Engineers. Atlanta, GA.

Azimi, Parham, Dan Zhao, and Brent Stephens. 2016. "Modeling the impact of residential HVAC filtration on indoor particles of outdoor origin (RP-1691)." *Science and Technology for the Built Environment*:1-32. doi: 10.1080/23744731.2016.1163239.

Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, W. F. Buhl, Y. Joe Huang, Curtis O. Pedersen, Richard K. Strand, Richard J. Liesen, Daniel E. Fisher, Michael J. Witte, and Jason Glazer. 2001. "EnergyPlus: creating a new-generation building energy simulation program." *Energy and Buildings* 33 (4):319-331. doi: http://dx.doi.org/10.1016/S0378-7788(00)00114-6.

Deru, Michael, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini, Bing Liu, Mark Halverson, Dave Winiarski, and Michael 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.

Dols, W. Stuart, Steven J. Emmerich, and Brian J. Polidoro. 2016. "Coupling the Multizone Airflow and Contaminant Transport Software CONTAM with EnergyPlus using Co-simulation." *Building Simulation* 9:469-479. doi: 10.1007/s12273-016-0279-2.

Fabian, Maria Patricia, Sharon Kitman Lee, Lindsay Jean Underhill, Kimberly Vermeer, Gary Adamkiewicz, and Jonathan Ian Levy. 2016. "Modeling Environmental Tobacco Smoke (ETS) Infiltration in Low-Income Multifamily Housing before and after Building Energy Retrofits." *International journal of environmental research and public health* 13 (3):327.

Fabian, Patricia, Gary Adamkiewicz, and Jonathan I Levy. 2012. "Simulating indoor concentrations of NO2 and PM2. 5 in multifamily housing for use in health-based intervention modeling." *Indoor Air* 22 (1):12-23.

Levy, Jonathan I., May K. Woo, and Yann Tambouret. 2016. "Energy savings and emissions reductions associated with increased insulation for new homes in the United States." *Building and Environment* 96:72-79. doi: 10.1016/j.buildenv.2015.11.008.

Ng, Lisa C, Amy Musser, Andrew K. Persily, and Steven 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.

Ng, Lisa C., Nelson Ojeda Quiles, W. Stuart Dols, and Steven J. Emmerich. 2018. "Weather correlations to calculate infiltration rates for U. S. commercial building energy models." *Building and Environment* 127 (Supplement C):47-57. doi: https://doi.org/10.1016/j.buildenv.2017.10.029.

Nouidui, Thierry, Michael Wetter, and Wangda Zuo. 2013. "Functional mock-up unit for co-simulation import in EnergyPlus." *Journal of Building Performance Simulation* 7 (3):192-202. doi: 10.1080/19401493.2013.808265.

Teichman, Kevin Y., Andrew K. Persily, and Steven J. Emmerich. 2015. "Indoor air quality in high-performing building case studies: Got data?" *Science and Technology for the Built Environment* 21 (1):91-98. doi: 10.1080/10789669.2014.976509.