NATIONAL RENEWABLE ENERGY LABORATORY






# Evaluating EnergyPlus Airflow Network Model for Residential Ducts, Infiltration, and Interzonal Airflow

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September 30, 2016

NREL/PR-5500-70230

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

# Context

| | |
|---|---|
| **Objective** | • Develop tools that accurately predict residential building energy use and occupant thermal comfort |
| **Activities** | • Evaluate and assess EnergyPlus Airflow Network modeling capabilities |
| **Output** | • Assessment of the EnergyPlus Airflow Network<br>• Recommended enhancements to meet residential building modeling needs |
| **Short Term Outcome** | • BEopt adoption of the EnergyPlus Airflow Network to eliminate current modeling work arounds |
| **Long Term Outcome** | • Improved modeling capabilities at predicting residential building thermal comfort |
| **Impact** | • Better duct and whole building air sealing have the potential to save up to 360 (2% of US single-family detached) and 258 TBtus/yr (1.5%), respectively |

# Outline

- Background
  - Current BEopt Approach
  - Airflow Network
- Assessment Approach
- Assessment Results
  - Ducts
  - Living Zone Infiltration
  - Attic Zone Infiltration
  - Interzonal Airflow
- Conclusions

# Background:
# Current BEopt Approach

# Background: Current BEopt Approach

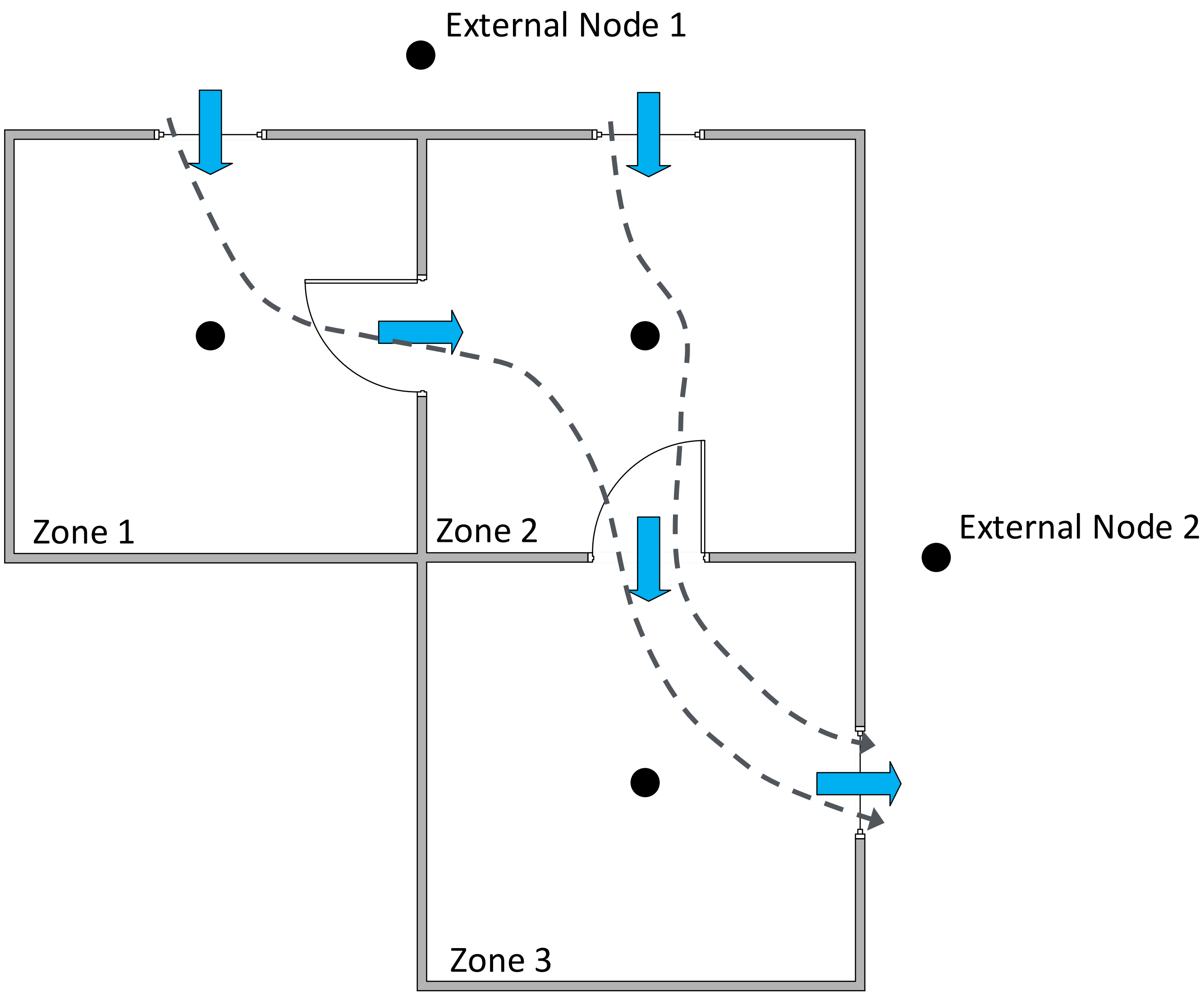
- Uses EnergyPlus Energy Management System (EMS)
  - EMS allows custom code to be executed during a timestep
  - EMS can read/modify internal EnergyPlus variables
- EMS-based model includes several capabilities
  - Infiltration via AIM-2 model
  - Duct conduction via log mean temperature difference
  - Duct leakage
  - Natural ventilation (open windows)
  - Imbalanced/balanced mechanical ventilation
  - Combining all of the above

# Background:
# Airflow Network

# Background: Airflow Network

- Physics-based airflow model
  - Based on NIST AIRNET model (Walton 1989)
  - Consists of a set of nodes linked by airflow components
    - Node variable: pressure
    - Linkage variable: airflow rate
  - Accounts for pressurization/depressurization of zones
  - Simplified model compared to detailed CFD models
- Two main aspects of the model
  - Infiltration/multi-zone airflow model
    - Cracks, leakage area, windows, doors, and stairwells
  - Duct model
    - Supply and return leaks and conduction losses
    - Impacts multi-zone airflow via return airflow

# Background: Airflow Network



# Background: Airflow Network

| | | EnergyPlus AFN | BEopt via EMS |
|---|---|---|---|
| Infiltration | Air leakage through cracks | Per Surface | Whole Building |
| | Dependency on wind velocity | ✓ | ✓ |
| | Dependency on wind direction/surface orientation | ✓ | ✗ |
| | Natural ventilation through open windows | ✓ | ✓ |
| | Interaction w/ mechanical ventilation | Zone Pressure | Quadrature |
| | Accounts for flues | ✗ | ✓ |
| Inter-zone | Airflow through doors, cracks, stairwells | ✓ | ✗ |
| | Interzonal mixing due HVAC system operation | ✓ | ✗ |
| Ducts | Conduction and air leakage losses, supply & return | Multiple Zones | Single Zone |
| | Supports multiple HVAC systems | ✗ | ✓ |
| | Supports multi-zone simulations | ✓ | ✗ |
| | Affects supply air temperature | ✓ | ✗ |
| Other | Zone air circulation/temperature stratification | ✗ | ✗ |
| | Pollutant transport | ✗ | ✗ |
| | Multi-zone balanced (ERV) ventilation | ✗ | ✗ |

# Background: Airflow Network

- Why Use It?
  - Eliminates BEopt EMS workarounds
  - Supports substantially more situations/details
  - Leverages ongoing E+ investments/development
- Why Not Use It?
  - Increases runtime speed
  - Requires more inputs
  - Requires data that can be hard to find in the literature

# Assessment Motivation

- Residential airflow modeling seen as one of highest-priority deficiencies in E+
- Growing stakeholder interest in using the Airflow Network model
  - NREL, ORNL, Fraunhofer
  - Bonneville Power Administration
  - California Public Utilities Commission
- Obstacles prevent widespread adoption
  - Unknown accuracy, speed, robustness
  - Unclear how best to use in a generalized tool
  - Usability concerns

# Assessment Approach

# Assessment Approach

**Goal: Systematically assess specific features of the EnergyPlus Airflow Network model**

## Assessed

- Duct model
- Living zone infiltration
  - Wind-driven
  - Stack-driven
  - w/ and w/o exhaust mechanical ventilation
- Attic zone infiltration
  - Stack-driven
  - Wind-driven
- Interzonal air mixing
- Usability

## Not Yet Assessed

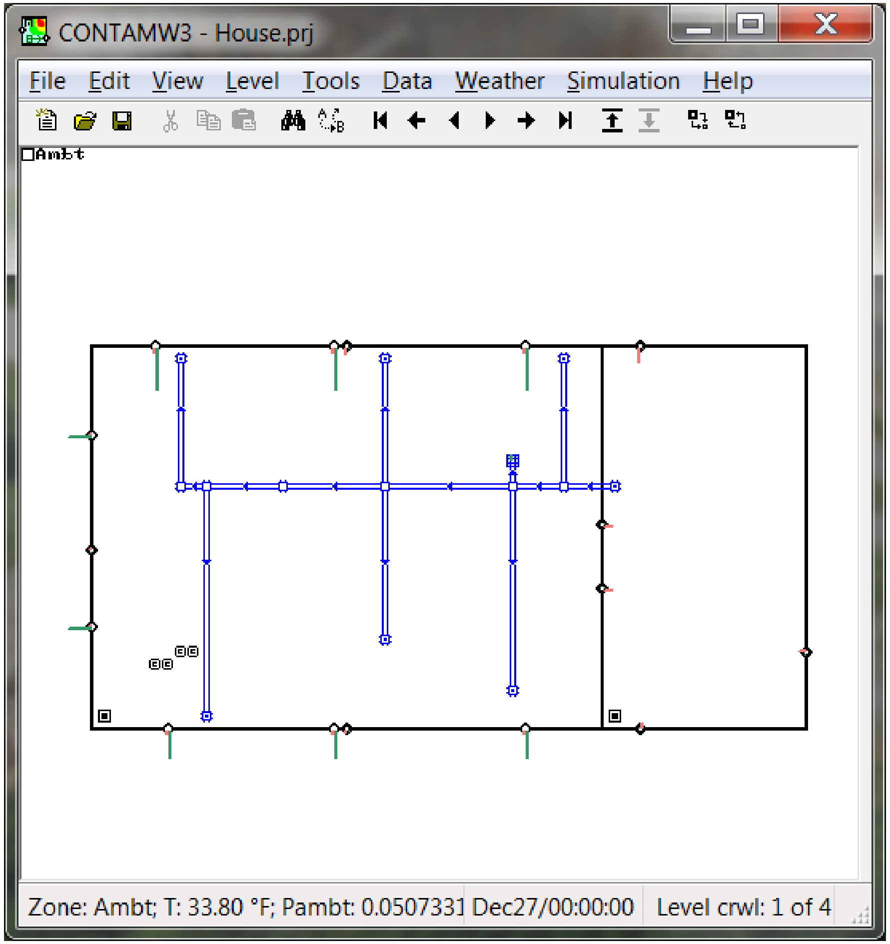
- Integrated supply fan ventilation system
- Integration with zone energy recovery ventilation system
- Imbalanced duct leakage interaction with infiltration and interzonal mixing

# Assessment Approach

- Compared EnergyPlus Airflow Network to CONTAM and BEopt Energy Management System (EMS) approach
  - Important to have equivalent models!
    - Wind pressure coefficients, wind velocity modifiers, leakage path areas, leakage path heights, mechanical ventilation rates, etc.
    - EnergyPlus zone temperatures manually set in CONTAM via Continuous Value Files
- Stack- and wind-driven effects analyzed separately
  - Wind-driven
    - Set ambient and sky temperatures equal to indoor temperature
    - Set global, horizontal, and direct normal radiation to zero
  - Stack-driven
    - Set wind speed to zero
    - Requires leakage paths at different heights
- Single building geometry simulated for one month in one climate

# Assessment Approach

- CONTAM is a multi-zone IAQ and ventilation analysis tool:
  - Airflows: infiltration, exfiltration, room-to-room airflows driven by natural and mechanically driven effects
  - Contaminant concentrations
  - Personal exposure
- CONTAM is not a thermal building model
  - Tool can be integrated with TRNSYS
- Free tool offered by NIST

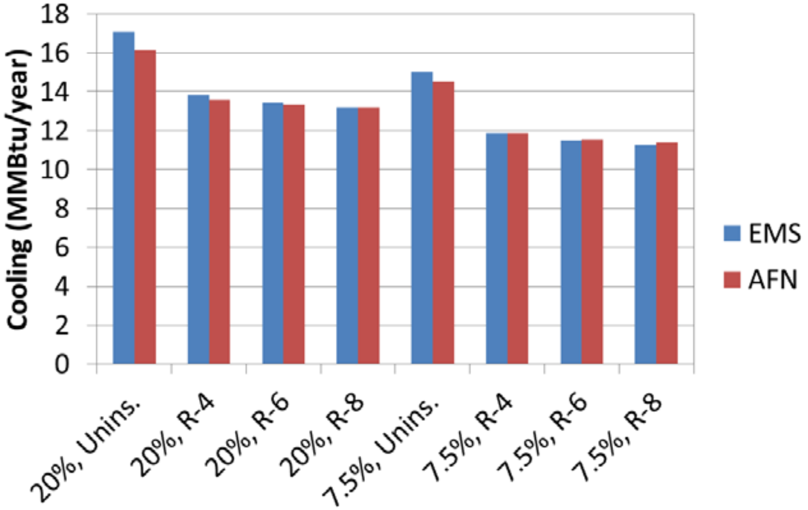


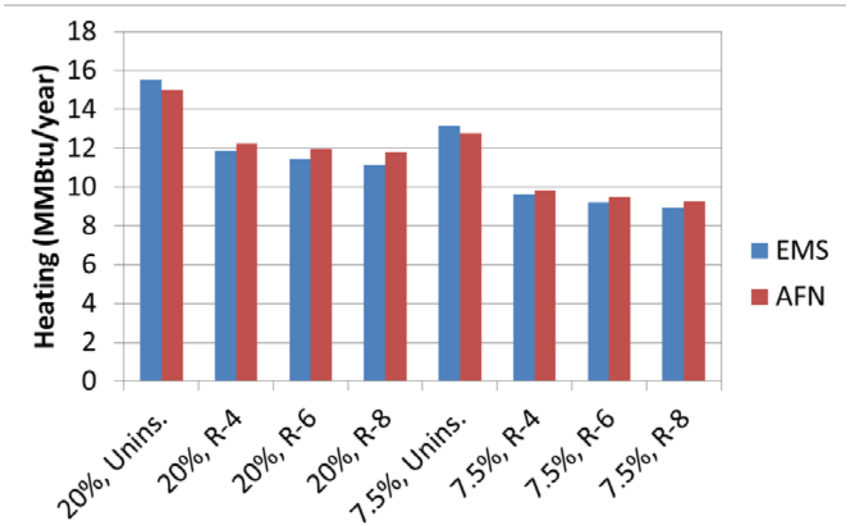
# Assessment Results: Ducts

# Ducts

- Identified several bugs to be fixed by EnergyPlus development team
  - Model has seen limited use despite being available since 2007

- Reasonable agreement with BEopt's current EMS-based duct model for varying insulation levels and leakage rates



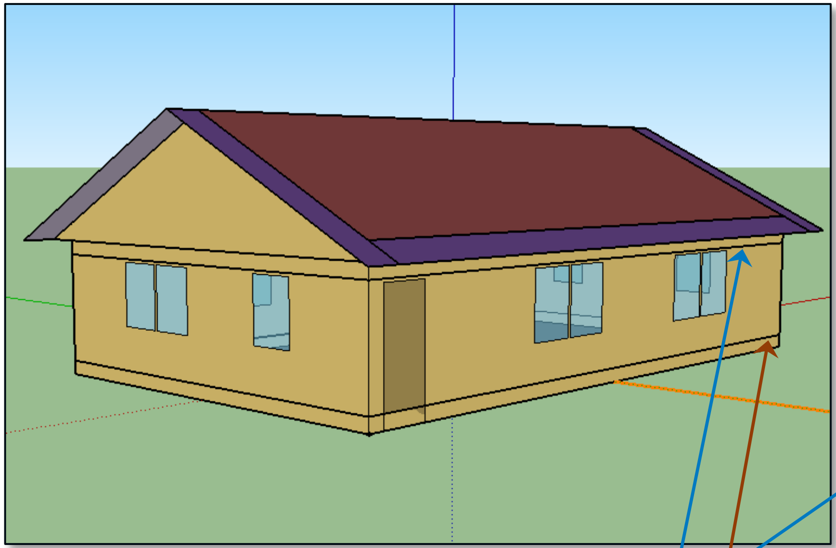
# Assessment Results:
# Living Zone Infiltration

# Living Zone Infiltration: Building Description

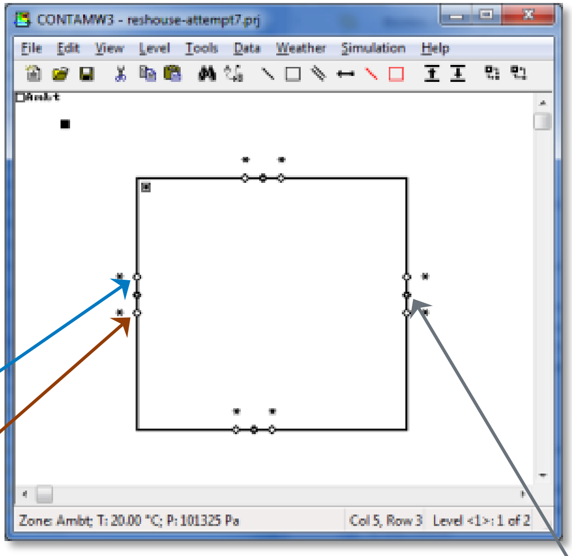
- Two zone model
  - One living zone & attic zone
- No interzonal airflow
- No mechanical ventilation

- Leakage apportioned based on façade area (equally divided low and high)

EnergyPlus Model



CONTAM Model




High Airflow Path

Low Airflow Path

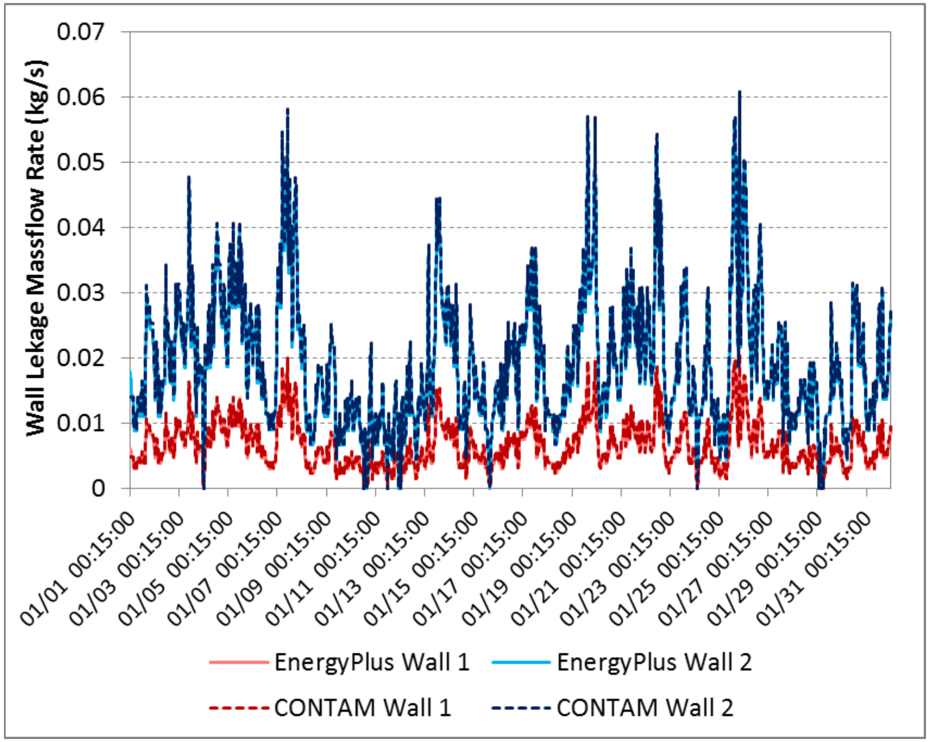
"Dummy" Leakage Path
(used for initially creating/testing the model)

# Living Zone Infiltration: Comparison

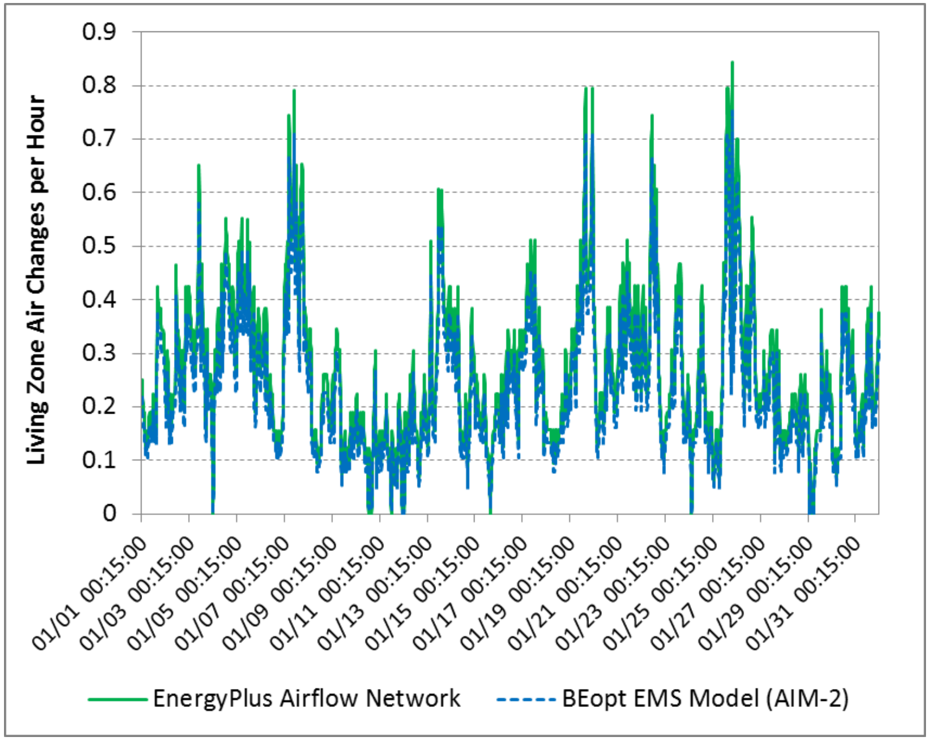
**Test Conditions**
- Wind speed: TMY Data
- Wind direction: Constant @ 0°
- Outdoor temperature: Constant @ 24.4°C
- Sky temperature: Constant @ 24.4°C
- Solar Radiation: Constant @ 0

**Comparison Metrics**
- CV(RSME) for walls 1 and 2 between EnergyPlus AFN and CONTAM
- CV(RSME) for living zone ACH between EnergyPlus AFN and BEopt EMS implementation of AIM-2 model

**EnergyPlus Airflow Network & CONTAM**




**EnergyPlus Airflow Network & BEopt EMS**



# Living Zone Infiltration: Results

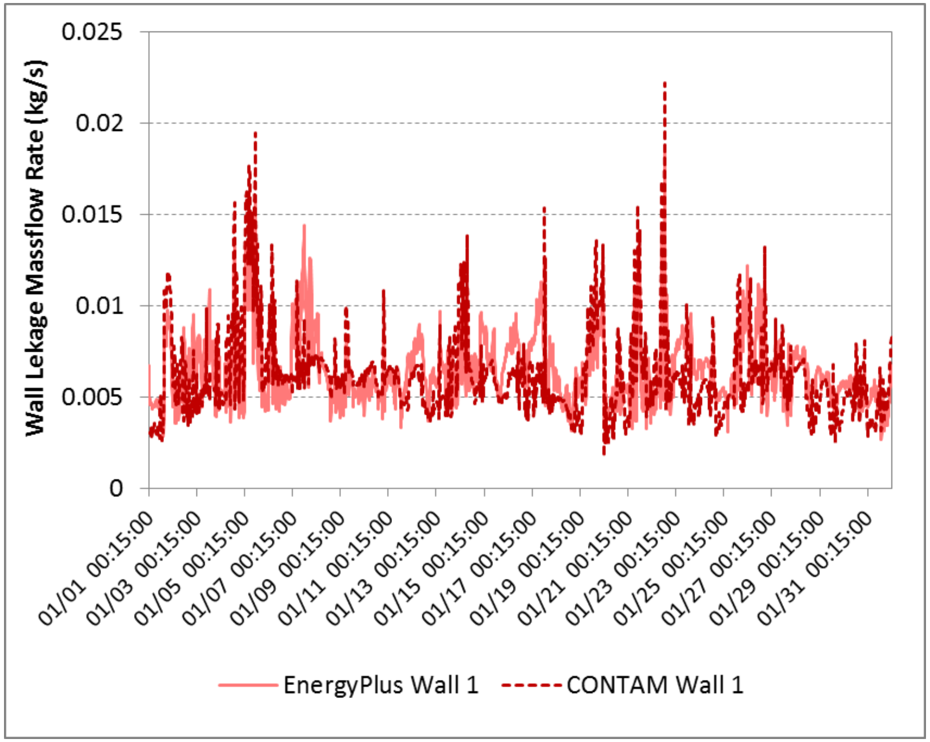
| | | | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|---|---|
| Test Case Inputs | Test Case | | Wind | Wind | Wind | Stack | Both |
| | Wind Speed | | 5 m/s | TMY | 5 m/s | 0 m/s | TMY |
| | Wind Direction | | 0° | 0° | TMY | N/A | TMY |
| | Ambient Temperature | | 24.4°C | 24.4°C | 24.4°C | TMY | TMY |
| | Sky Temperature | | 24.4°C | 24.4°C | 24.4°C | TMY | TMY |
| | Solar Radiation | | 0 | 0 | 0 | TMY | TMY |
| Results | AFN & CONTAM | Wall 1 MFR CV(RSME) | 0.03 | 0.04 | 0.05 | 0.09 | **0.25** |
| | | Wall 1 MRF Monthly % Diff. | -3% | -3% | 8% | 8% | 3% |
| | | Wall 2 MRF CV(RSME) | 0.03 | 0.04 | 0.05 | 0.06 | **0.30** |
| | | Wall 2 MRF Monthly % Diff. | -3% | -3% | -3% | 3% | 5% |
| | AFN & BEopt | Living Zone ACH CV(RSME) | 0.15 | 0.16 | 0.15 | 0.25 | 0.13 |
| | | Living Zone ACH Monthly % Diff. | 15% | 15% | 1% | 24% | -4% |

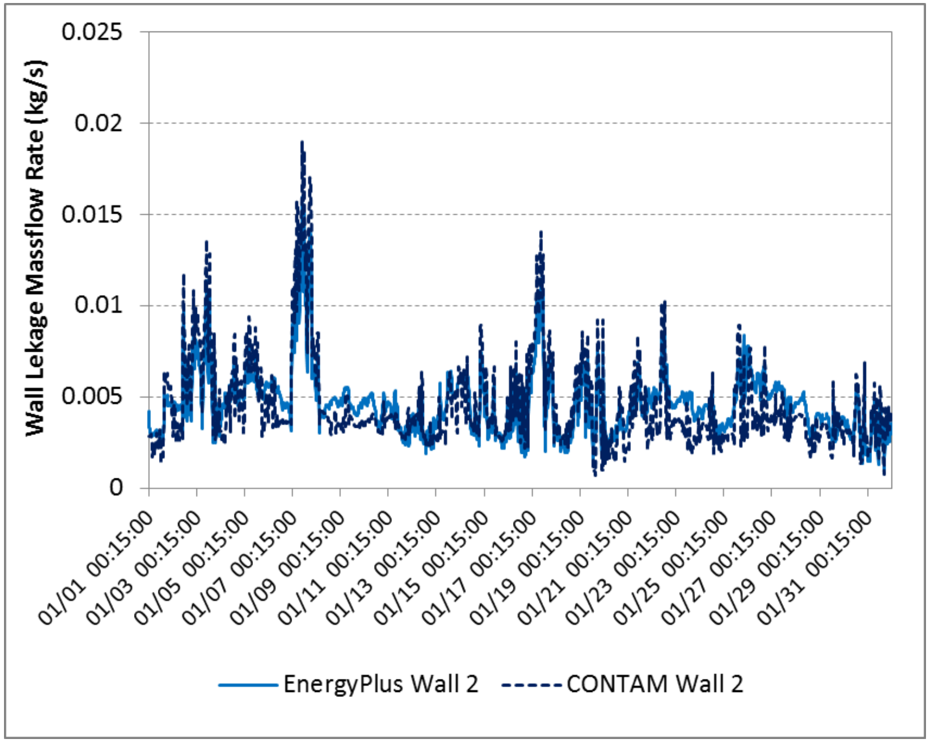
# Living Zone Infiltration: Case 5

**Test Conditions**
- Wind speed: TMY Data
- Wind direction: TMY Data
- Outdoor temperature: TMY Data
- Sky temperature: TMY Data
- Solar Radiation: TMY Data

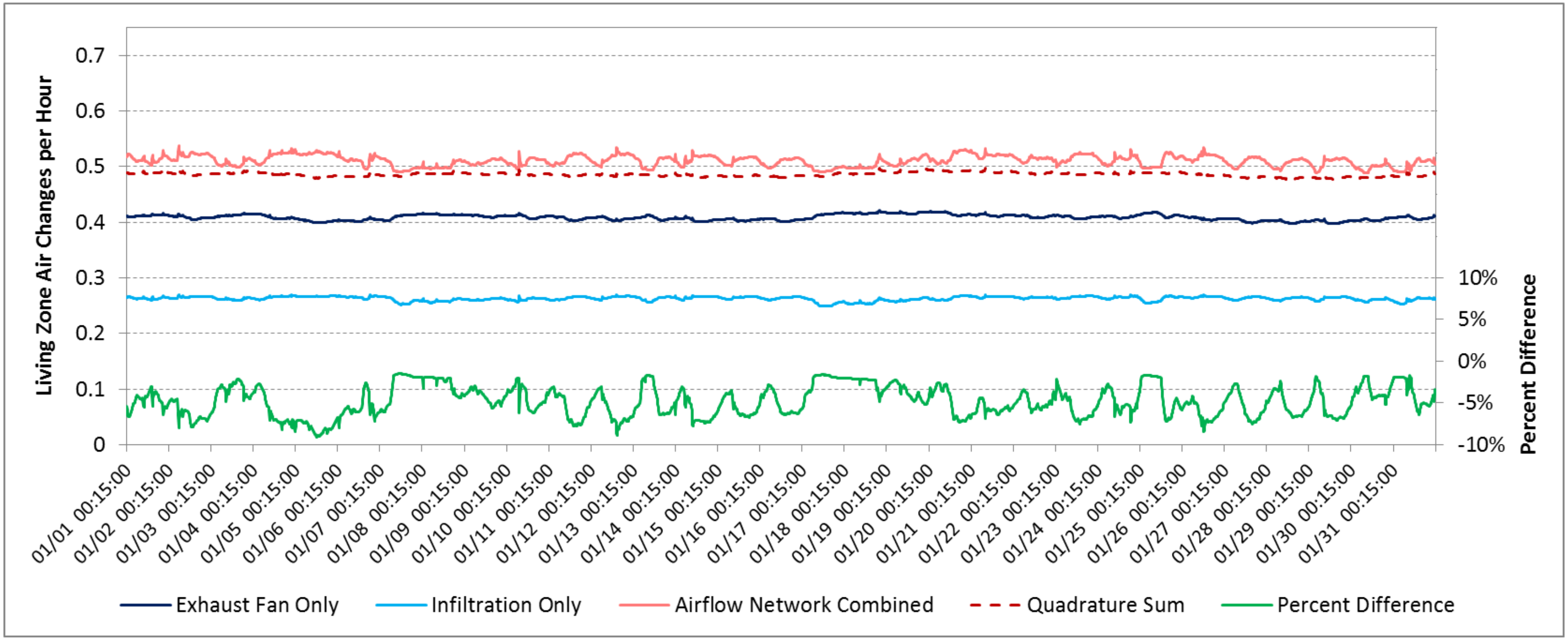
**Results**
- Wall 1 CV(RSME) = 0.25
- Wall 2 CV(RSME) = 0.30
- Despite higher CV(RSME) values compared to other tests, time series plots show acceptable agreement

## EnergyPlus Airflow Network & CONTAM



# Living Zone Infiltration: With Mechanical Ventilation




- Exhaust fan models zone depressurization
  - Use of schedules accounts for periodic spot exhaust fan operation
- Combining natural infiltration and exhaust mechanical ventilation closely aligns with quadrature assumption

# Living Zone Infiltration: Summary

- EnergyPlus Airflow Network compares well to both CONTAM and the BEopt EMS implementation of the AIM-2 model
  - Summing the total infiltration over the 1-month simulation period shows very good agreement
- Equally apportioning whole building leakage based on façade area seems appropriate when comparing to whole-building infiltration models

# Assessment Results:
# Attic Zone Infiltration

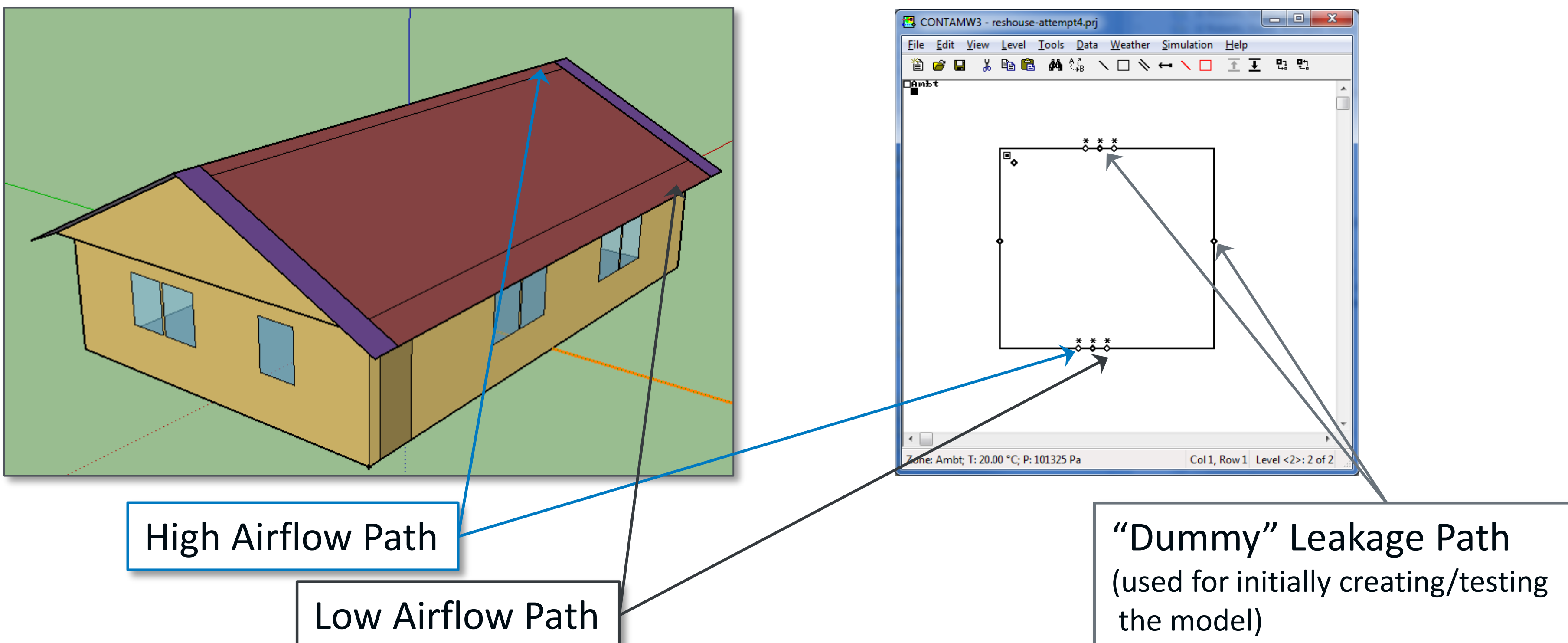
# Attic Zone Infiltration: Building Description

- Two zone model
  - One living zone & attic zone
- No interzonal airflow
- No duct system

- Leakage area equally apportioned low and high
  - Required for stack-induced ventilation

EnergyPlus Model

CONTAM Model



# Attic Zone Infiltration: Results

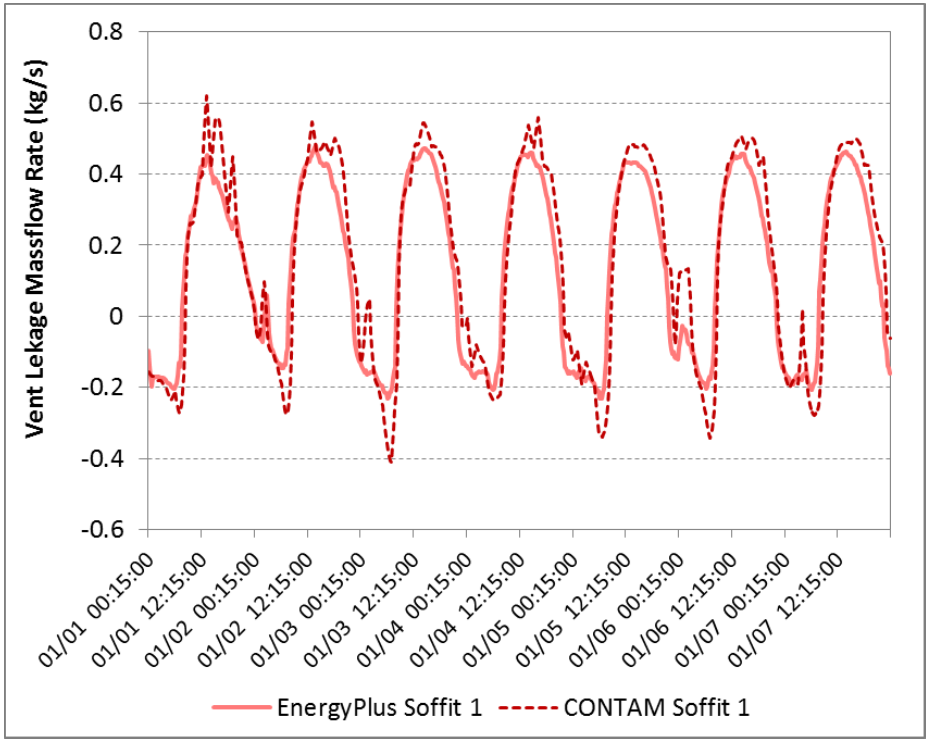
| | | | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|---|---|
| Test Case Inputs | Test Case | | Wind | Wind | Wind | Stack | Both |
| | Wind Speed | | 5 m/s | TMY | TMY | 0 m/s | TMY |
| | Wind Direction | | 0° | 0° | TMY | N/A | TMY |
| | Ambient Temperature | | 24.4°C | 24.4°C | 24.4°C | TMY | TMY |
| | Sky Temperature | | 24.4°C | 24.4°C | 24.4°C | TMY | TMY |
| | Solar Radiation | | 0 | 0 | 0 | TMY | TMY |
| Results | AFN & CONTAM | Soffit Vent MFR CV(RSME) | 0.03 | 0.03 | 0.03 | **0.29** | N/A |
| | | Soffit Vent MRF Monthly % Diff. | -3% | -3% | -3% | -13% | N/A |
| | | Ridge Vent MRF CV(RSME) | 0.03 | 0.03 | 0.03 | **0.28** | N/A |
| | | Ridge Vent MRF Monthly % Diff. | -3% | -3% | -3% | -13% | N/A |
| | AFN & BEopt | Attic Zone ACH CV(RSME) | N/A | N/A | N/A | N/A | **0.29** |
| | | Attic Zone ACH Monthly % Diff. | N/A | N/A | N/A | N/A | 42% |
| | | Attic Zone Temperature CV(RSME) | N/A | N/A | N/A | N/A | **0.10** |

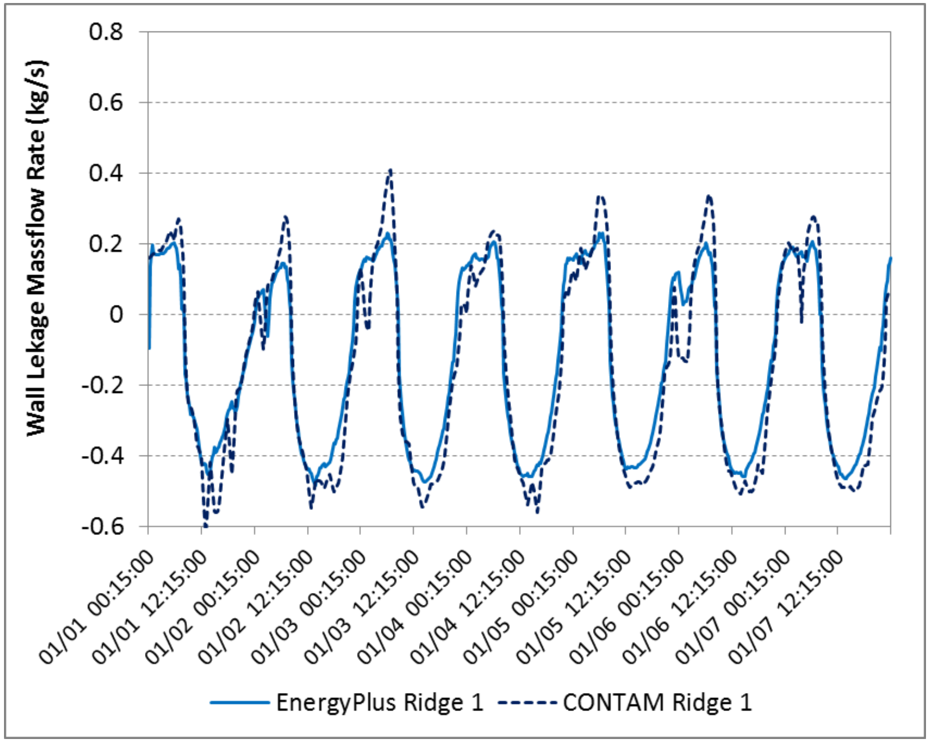
# Attic Zone Infiltration: Case 4

**Test Conditions**
- Wind speed: 0 m/s
- Wind direction: N/A
- Outdoor temperature: TMY Data
- Sky temperature: TMY Data
- Solar Radiation: TMY Data

**Results**
- Soffit CV(RSME) = 0.29
- Ridge CV(RSME) = 0.28
- Time series plots show acceptable agreement
- CONTAM results show irregular spikes

## EnergyPlus Airflow Network & CONTAM



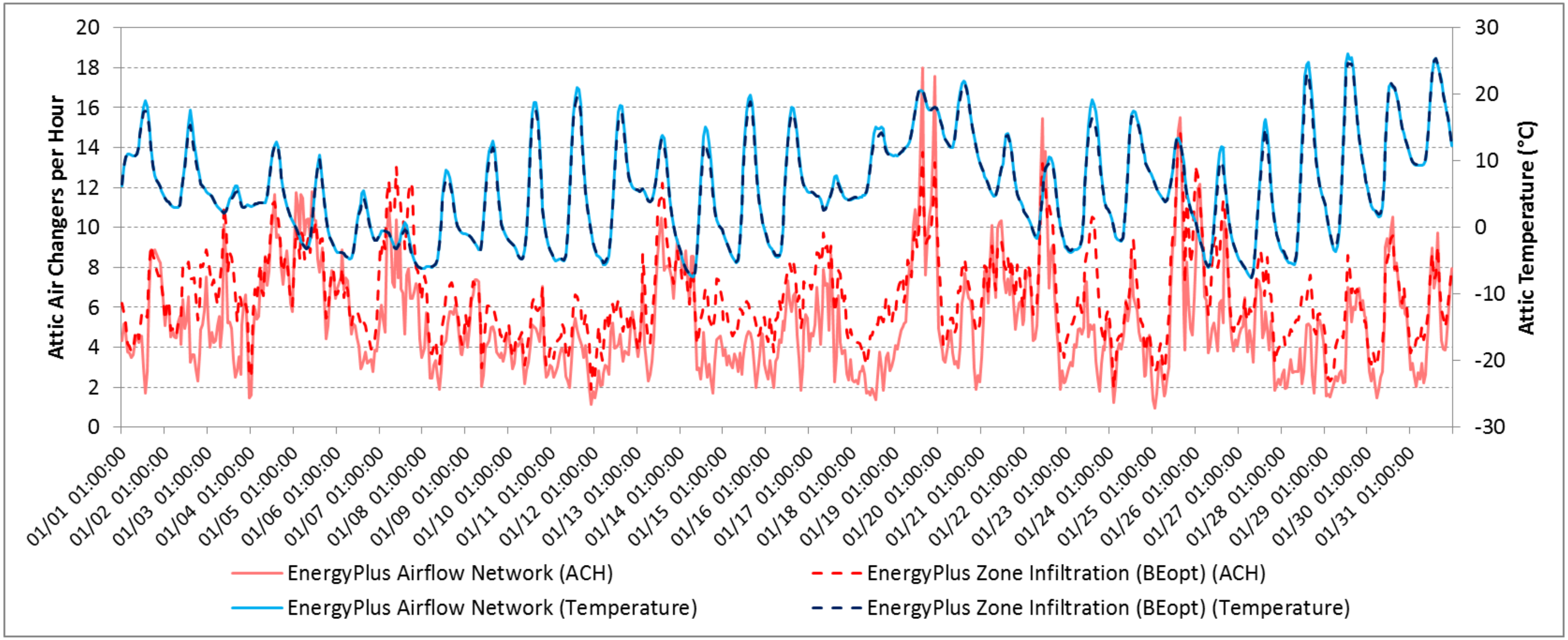



# Attic Zone Infiltration: Case 5

**Test Conditions**
- Wind speed: TMY Data
- Wind direction: TMY Data
- Outdoor temperature: TMY Data
- Sky temperature: TMY Data
- Solar Radiation: TMY Data

**Results**
- Attic ACH CV(RSME) = 0.29
- Temperature CV(RSME) = 0.10
- Despite poor agreement in ACH, temperature predictions closely align

## EnergyPlus Airflow Network & EnergyPlus Zone Infiltration



# Attic Zone Infiltration: Summary

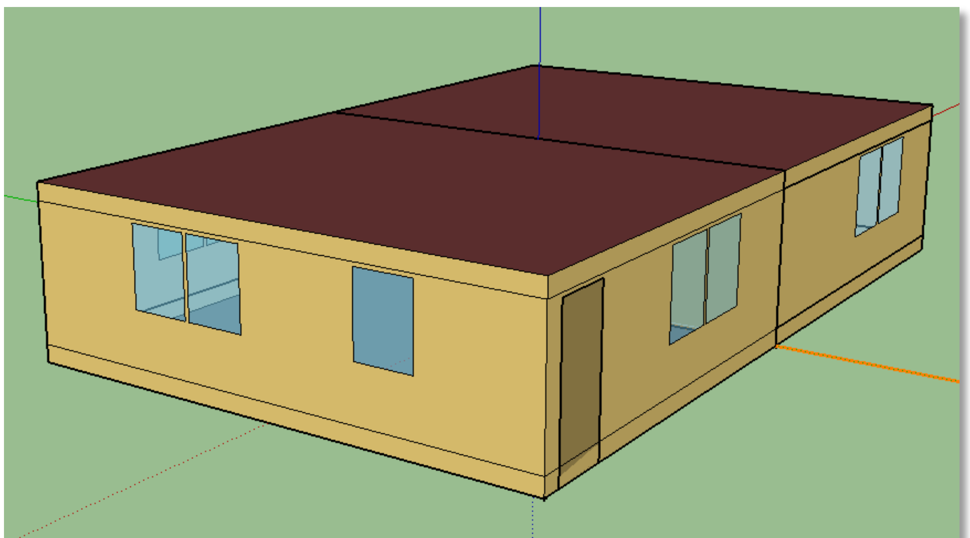
- EnergyPlus Airflow Network compares well to both CONTAM and BEopt’s use of the EnergyPlus Zone Infiltration (Sherman-Grimsrud) model
  - Summing the total infiltration over the 1-month simulation period shows very good agreement
- Equally apportioning attic leakage between soffit and ridge vents seems appropriate when comparing to whole-building infiltration models

# Assessment Results:
# Interzonal Airflow

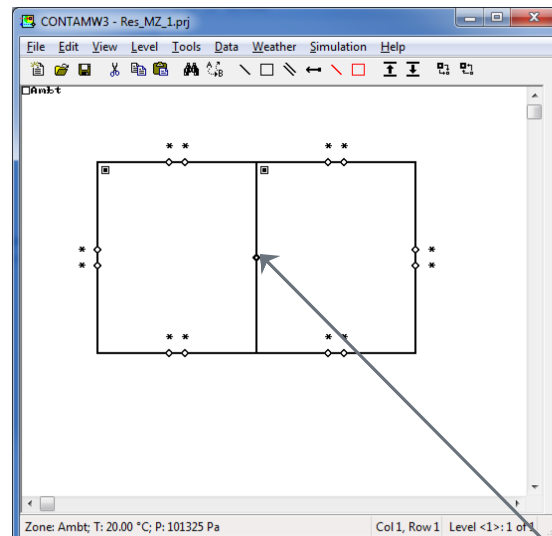
# Interzonal Airflow: Building Description

- Two living zone model
  - Supply air to both zones
  - Thermostat in zone 1
- Includes interzonal airflow
- No duct system
- Compared interzonal airflow due to wind and temperature driven effects

EnergyPlus Model



CONTAM Model




Interzonal Air Path

# Interzonal Airflow: Results

| | | | Case 1 | Case 2 |
|---|---|---|---|---|
| Test Case Inputs | Wind Speed | | 5 m/s | 5 m/s |
| | Wind Direction | | 90° | TMY |
| | Ambient Temperature | | 24.4°C | 24.4°C |
| | Sky Temperature | | 24.4°C | 24.4°C |
| | Solar Radiation | | 0 | 0 |
| Results | AFN & CONTAM | Interzonal MFR CV(RSME) | 3% | 1% |
| | | Interzonal MRF Monthly % Diff. | 0.03 | 0.30 |

# Interzonal Airflow: Case 2

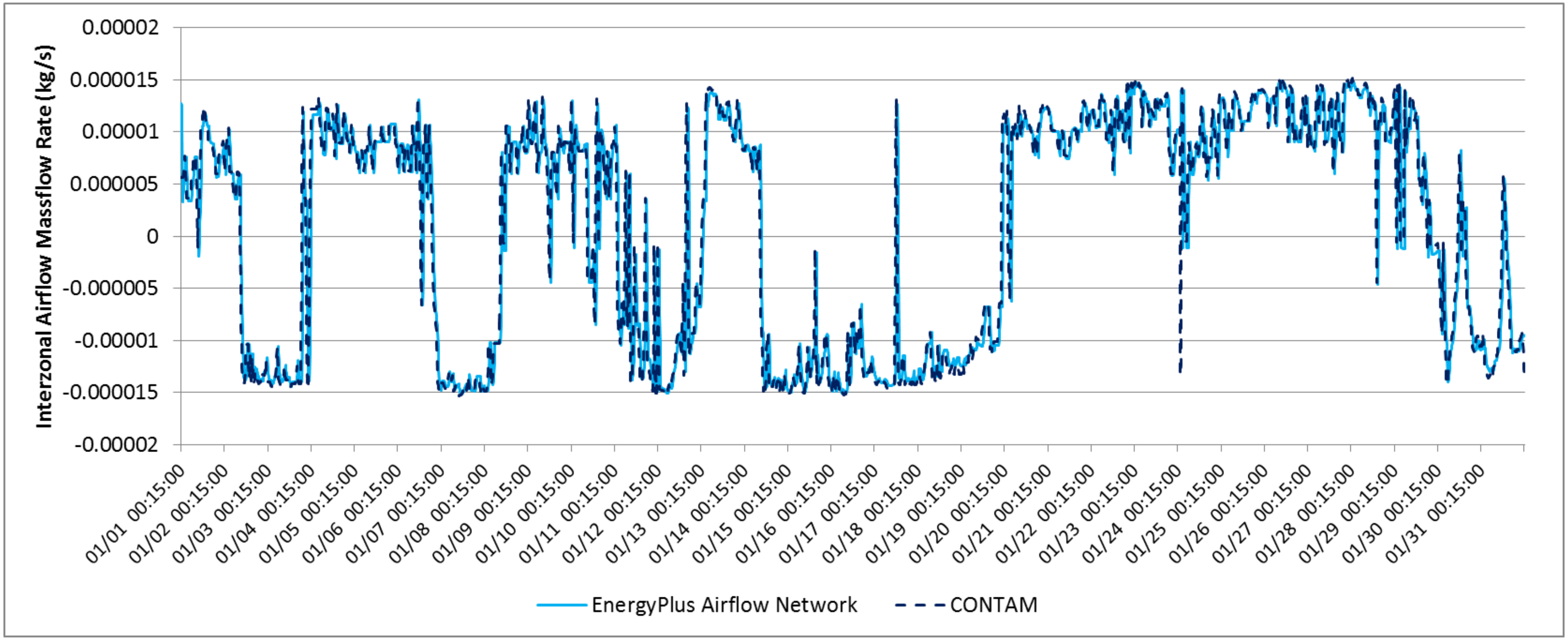
**Test Conditions**

- Wind speed: Constant @ 5 m/s
- Wind direction: TMY
- Outdoor temperature: Constant @ 24.4°C
- Sky temperature: Constant @ 24.4°C
- Solar Radiation: Constant @ 0

**Results**

- Interzonal MFR CV(RSME) = 0.29
- Hourly results show close agreement

**EnergyPlus Airflow Network & CONTAM Interzonal Airflow**



# Conclusions

# Conclusions

- Airflow Network showed good agreement with CONTAM and BEopt approaches
- Airflow Network provides substantially more capabilities and detail than current BEopt approach
- Assessment indicates BEopt could likely start using Airflow Network; however:
  - Systematic assessment of simulation runtime was not conducted
  - OpenStudio does not currently accommodate Airflow Network

# Recommended Enhancements/Fixes (High Priority)

| Title | Description |
|---|---|
| **Add Model for Zone Induced Air by a Constant Volume Fan** | This will allow EnergyPlus to model 1) transfer fans, and 2) Case MA204 of the IEA Multi-zone air flow test suite. |
| **Improve Radiant and Convective Heat Transfer Physics Relevant to Ducts Located in Ventilated Attics** | Add radiation exchange between duct surfaces and zone surfaces and improve convective heat exchange correlations. (Effort underway by Fraunhofer.) |
| **Allow Multiple Air Primary Loops in the Airflow Network Model** | This is the number one shortcoming of AFN in terms of user perception and is required to model multi-family residential buildings. |
| **Allow Multiple Leakage Components Per Surface** | This will enable better simulation of stack-type phenomena without the requirement that heat transfer surfaces be broken up to accommodate multiple leakage paths |
| **Use E+ Curves for Reusable Wind Pressure Profiles** | This would greatly simplify model development, allowing models to specify a single, generic curve rather than the current, somewhat cumbersome, input. |
| **Wind Pressure Coefficients Auto-Calculate** | Improve AFN wind pressure coefficient auto-calculate ability. |
| **Duct Autosizing** | This would help users determine AFN inputs and ensure the desired amount of air is being delivered to a particular zone. |
| **Return Air Path** | This would allow users to more easily simulate common residential building return air pathways. |
| **Relax Crack Factor Magnitude Restriction** | Current surface linkage limits crack flow multiplier to (0,1], limiting true reuse of leakage components. |
| **Performance Improvements; Refactor Solver** | Profile model; look for obvious solutions. Switch to different solver. |

# Recommended Enhancements/Fixes (Medium Priority)

| Title | Description |
|---|---|
| **Airflow Network Model: Air Distribution System Thermal Capacitance** | Energy losses from an air distribution system in the Airflow Network model are calculated based on a steady-state condition when the supply fan turns on, and are assumed to be zero when the fan is off. This assumption neglects losses from the air distribution system during the system off periods. |
| **Include a Dedicated Supply Fan** | This would allow for simulation of dedicated supply fans for residential buildings. |
| **Distributed ERV model** | This will enable users to simulate an standalone, distributed ERV apart from the central supply fan, which is a common installation practice for residential buildings. |
| **Relax Air Node Requirements** | This will improve AFN usability. Currently AFN requires a mirrored copy of every system air node. This results in an unnecessary amount of nodes and linkages. |

# List of Participants

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Thank you!

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