

A NOVEL APPROACH TO MODELLING AIR FLOW THROUGH OPERABLE WINDOWS IN HIGH-RISE MULTI-UNIT RESIDENTIAL BUILDINGS USING ENERGY PLUS

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ABSTRACT

Residents often open their windows to promote natural ventilation in attempts to achieve comfortable indoor temperatures, which can have significant energy impacts. In EnergyPlus, there are two typical window air flow modelling techniques, which utilize the following objects: 1) *ZoneVentilation:WindandStackOpenArea*, and 2) *AirFlowNetwork*. While the first object is simple to implement, it can produce unrealistic results. The second object has produced accurate results in other studies, but the required inputs can be impractical to attain. This study proposes an alternative modelling technique in EnergyPlus where the window is modelled as an economizer. This technique was applied in the simulation of a case study building in Toronto, Canada, to demonstrate that more stable air flow rates and interior temperatures could be achieved using the economizer model through the heating season. These results yield a more realistic representation of the effect of window opening on building performance.

INTRODUCTION

The use of operable windows to increase ventilation rates and achieve natural cooling is often implemented in buildings ranging from single-family homes to high-rise towers (Gil-Baez, Barrios-Padura, Molina-Huelva, & Chacartegui, 2017). This 'free' cooling method allows occupants to reduce indoor temperatures without significant energy expenditure during the cooling season, reducing overall building energy consumption. However, this cooling method is also used during the heating season in buildings that experience overheating due to poor heating system control (Fine & Touchie, 2019). The use of windows in this case results in increased heating energy consumption due to increased infiltration or exfiltration through the open window. This scenario occurs frequently in post-war multi-unit residential buildings (MURBs), which are often heated with a central boiler plant and hydronic radiators without in-suite control. The central boiler typically supplies hot

water to each radiator at a constant rate, and the supply temperature is only varied as a function of the outdoor temperature. In many cases, occupants do not have any method to reduce the heat output of the radiators in their suite, resulting in overheating even at low exterior temperatures during the heating season (Diaz Lozano Patiño, Vakalis, Touchie, Tzekova, & Siegel, 2018). Therefore, being able to capture the effect of window operation on building performance is important to accurately model building performance in these cases.

When modelling operable windows in buildings, there are two factors that must be considered. The first focuses on predicting the behaviour of occupants as they operate their windows. This factor is an area of ongoing research, but is not the focus of this study. The second factor focuses on the implementation of a mathematical model that can predict mass and energy transfer as a result of window operation, which is the focus of this study.

As such, this study focusses on the development of a novel economizer-based modelling approach in EnergyPlus. First, two existing EnergyPlus modelling objects will be discussed in the next section to provide additional context for this new model. Next, details of the newly developed modelling technique are presented in the Methodology section, such that the reader can implement this model themselves. It is important to note that while EnergyPlus was the simulation engine used in this study, this modelling technique can be applied in other simulation environments. Finally, this modelling approach was implemented to analyze performance during the heating season for a building in Toronto, Canada, which is presented in the Case Study section.

EXISTING WINDOW MODELLING TECHNIQUES IN ENERGYPLUS

This section presents an overview of the two typically used operable window modelling techniques in EnergyPlus, with the goal of detailing the strengths and limitations of the existing options.

The *WindandStackOpenArea* Modelling Technique

The *WindandStackOpenArea* object models a simple opening of known size in a building envelope that can be fully open or fully closed, and is controlled using a differential temperature control strategy (United States Department of Energy (DOE), 2018). This object is relatively simple as very few input parameters are needed, but the binary nature of the window state can result in significant modelling errors, which are detailed in later sections. The effect of wind and stack on a building, which drive air flow through the opening, can be accounted for. The building characteristic inputs required for this object are the cross-sectional area of the opening, the wind discharge coefficient, the stack effect discharge coefficient, the height of the window above the neutral pressure plane of the building, and temperature setpoint parameters to govern the operable window control. Calculation of the two discharge coefficients can be carried out automatically by EnergyPlus at each simulation time step to account for the zone orientation relative to the wind velocity, and for the effectiveness of stack effect as a function of temperature. More information regarding the mathematical model of this object can be found in the EnergyPlus user guides (United States Department of Energy (DOE), 2018).

This object outputs the air flow rate through the window at each time step as a function of the wind speed, wind direction, and interior zone temperature. Based upon the outputs from this object, and other energy modelling input parameters, the interior temperature of the zone can be determined. Using this interior temperature, and comparing it to the outdoor temperature, the *WindandStackOpenArea* object will then determine if the window should be set to fully open or fully closed based upon the previously defined setpoints. This calculation method, when combined with the differential temperature control strategy, then allows for the final ventilation rate to be determined at each time step. However, when the interior zone volume is small relative to the resulting incoming air flow rate, the mean air temperature of the zone can change drastically over a short time period when the window is open.

To illustrate this issue, a sample simulation was carried out using this model in a single zone with a total operable window area of 1.5 m² (16 ft²), floor area of 46.4 m² (500 ft²), volume of 125 m³ (4,400 ft³), and heavy masonry construction. The results from this simulation yielded zone mean air temperature variations of up to 19°C (35°F) over a 10-minute time step since the window state can only be set to fully open or fully closed, resulting in undesirable and unrealistic indoor temperatures. Similarly, the method used to calculate the air flow rate when wind is present relies on the multiplication of the

wind velocity by the window area, which can result in extremely high air flow rates, even after the wind discharge coefficient is taken into account. These results are also not representative of the indoor temperatures our field measurements have shown, which exhibited only a 3°C (5.4°F) change over a one-hour period within one meter of a window. To account for these issues, energy modellers often implement an *AirFlowNetwork* (Schulze & Eicker, 2013). As such, the development of an *AirFlowNetwork* was considered as an alternative window modelling method and is discussed next.

The *AirFlowNetwork* Modelling Technique

An *AirFlowNetwork* refers to a group of objects in EnergyPlus that can be combined to represent air transfer between multiple zones within a building (United States Department of Energy (DOE), 2018). This network allows for the calculation of mass and energy transfer between each of these zones as a function of environmental and construction parameters. These objects allow for air flow to be driven by naturally induced pressures, such as wind and stack effect, along with forced air flow such as that induced by an HVAC system. To calculate naturally induced air flow within these networks, the model must include unique objects for each of the zones that can experience air exchange to the exterior and/or between each other. These zone objects require information about zone orientation, size, and ventilation control. Along with each of the zone objects, the pressure-flow performance of each zone air flow boundary must also be set (United States Department of Energy (DOE), 2018). Using these inputs, EnergyPlus can then determine the pressure and flow distribution within the flow network. Similarly, operable windows can be modelled within each zone, and the opening size can be modulated as a function of the exterior and interior temperatures, which makes this technique flexible and potentially highly representative of the actual building air flow distribution.

However, knowing the detailed flow characteristics of each component of the zone is often impractical, which limits the use of this modelling technique. For example, in a high-rise MURB, each suite will typically have five internal pressure boundaries, and one exterior pressure boundary. Then, the corridor that connects to each suite will also require pressure boundary characterization, including the leakage through elevator shafts and through other mechanical penetrations. Characterization of each of these components is not well documented in the literature, is labour intensive to collect, and makes the implementation of this modelling technique impractical in most cases.

To resolve these issues, some researchers have created simplified building *AirFlowNetworks* that utilize

assumed airflow characteristics, and neglect inter-zonal partitions and vertical shafts (Carlucci, Pagliano, & Sangalli, 2014; Wang & Greenberg, 2015). In addition, a review of the literature did not reveal any studies where a detailed model of a high-rise MURB was used.

To address the limitations of these existing models, the technique developed as part of this study aims to reduce the number of inputs needed, as compared to the *AirFlowNetwork*, while offering additional flexibility for window operation, as compared to the *WindandStackOpenArea*. Given the detailed building information required to create an *AirFlowNetwork*, the *AirFlowNetwork* was not tested as part of this study since the required information could not be attained. This inability to acquire information persisted even after several days of on-site testing, which serves as a limitation to this study, but also supports the need for a more practical modelling technique. Notwithstanding this limitation, a comparison of the proposed model against building energy use data and to the *WindandStackOpenArea* modelling technique was carried out to support model accuracy improvement claims, and is presented in the Case Study section. To continue, the modelling methodology is presented.

METHODOLOGY

This section begins with an overview of the proposed model, followed by the details of how to set up the required objects in EnergyPlus version 9.0.1, and finishing with details on how to calculate flow rates for the model in a high-rise MURB context.

Overview of Simple Economizer Systems

The technique that has been developed assumes that the operable window is modelled as an economizer, which uses outdoor air to cool an interior zone. It is important to reiterate that this economizer system is not physically installed in the real building and is a theoretical representation of an operable window. A basic schematic representation of this system is shown in Figure 1.

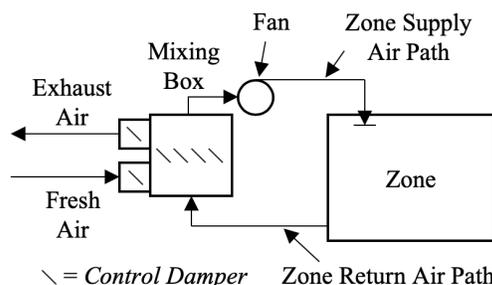


Figure 1: Schematic of Theoretical Economizer System

As shown in Figure 1, the economizer system circulates air through an air loop where the supply and return air

flow pathways are directly connected to the zone. Then, there is a mixing box where air is exhausted and taken in. It is assumed that the amount of exhaust air and incoming outdoor air are equal, which is meant to represent balanced airflow between the corridor and window through the suite, and the specific volumetric flow rate is selected in attempts to maintain a pre-defined indoor temperature. It is important to note that the schematic in Figure 1 does not include any energy recovery, conditioning equipment, or outdoor air pre-treatment as it is not meant to represent a fully-functional space conditioning system.

One critical feature of this model are limits that are placed on the minimum and maximum flow rates of outdoor air, which will be discussed in the Calculation of Outdoor Air Flow Limits section. The set up of this model for used in EnergyPlus is presented next.

Model Set Up in EnergyPlus

To set up this model in EnergyPlus, there are seven main objects that are required to create the air loop with an economizer. These objects are required for each thermal zone being simulated, which was assumed to be one zone per suite in this study, but multiple spaces can be combined if needed. Using an EnergyPlus template object may simplify the setup process, but the manual implementation of these components will be presented here. The require objects are: 1) *Zone*, 2) *Airloop:HVAC*, 3) *Fan:ConstantVolume*, 4) *OutdoorAir:Mixer*, 5) *Coil:Heating:Electric*, 6) *AirTerminal:SingleDuct:Uncontrolled*, and 7) *Controller:OutdoorAir*. Each of these objects are presented with the required connections in Figure 2.

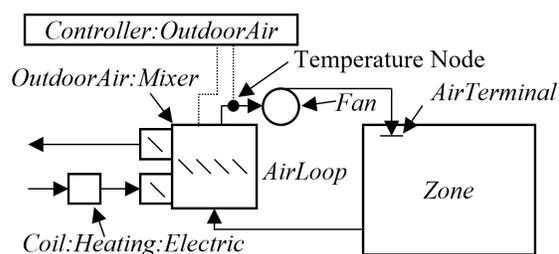


Figure 2: Layout of EnergyPlus Components

The *Zone* object represents the thermal zone in the building, which can be one or more highly connected spaces that have operable windows. This object is the only object from the above list that has a physical representation in the real-world, and the others are only implemented for simulation purposes. The details of setting up a thermal zone in EnergyPlus are outside the scope of this discussion, but more information can be

found in the EnergyPlus InputOutput manual, if needed (United States Department of Energy (DOE), 2018).

The *AirLoop:HVAC* object represents the theoretical air loop that is required to model the economizer system. This object is used to reference the overall air system that is being implemented, which contains lists of the other system equipment. The details of setting up this component are the same as in typical EnergyPlus simulations, and a detailed description of this object setup are also outside the scope of this study.

The *OutdoorAir:Mixer* object is used to intake fresh air while simultaneously exhausting the same volume of zone air from the *AirLoop*. It is important to note that the “fresh” air can represent both actual outdoor air and air from the corridor in this model, which will be discussed in more detail shortly. This fresh air is then mixed with the re-circulated *AirLoop* air, which is then used as the supply air to the zone. This supply air is then added to the zone using the *AirTerminal:SingleDuct:Uncontrolled*, which represents a theoretical diffuser within the space.

The *Controller:OutdoorAir* object is used to control the flow rate of incoming fresh and exhaust air that the *OutdoorAir:Mixer* object intakes and exhausts. The controller receives a temperature measurement from the air leaving the *OutdoorAir:Mixer* object, as indicated by the “Temperature Node” in Figure 2. The controller compares this air temperature to the zone setpoint and attempts to maintain this air temperature at the setpoint by increasing or decreasing the flow of fresh air within the previously mentioned limits. Since this controller is required to measure the temperature of the air leaving the mixer at the location indicated in Figure 2, which must be representative of the zone mean air temperature, the total air loop flow rate must be selected to allow for accurate zone mean air temperature representation. The details of this flow rate selection are discussed next.

The *Fan:ConstantVolume* object is used to circulate air through the theoretical air loop, and the input parameters for this object define the total air flow rate through the air loop. As previously mentioned, this air flow rate must be selected such that the temperature at the Temperature Node shown in Figure 2 represents the zone mean air temperature. Through trial and error, and while using the default EnergyPlus simulation time step of 10-minutes, it was found that setting this flow rate to approximately 10% of the total zone air volume per second allowed for the Temperature Node measurement to be representative of the mean zone temperature, and further increases did not significantly change the simulation result. Note that this value is only a guide and is specific to the zone modelled as part of this study. When using this model for other zones, it is important to ensure that the simulation

results are not sensitive to this air flow rate. As such, a sensitivity analysis should always be conducted. Since the fan is theoretical and does not exist in the real building, it is also important to set the energy consumption of the fan to zero to ensure that the fan energy consumption it is not added to the overall building energy consumption, and that heat is not being transferred from the fan to the air stream.

Finally, this system must be able to simulate both infiltration and exfiltration, where the air added to a zone originates from the outdoors or other interior zones, respectively. However, EnergyPlus requires that an outdoor air node be assigned to the fresh air stream field for an *OutdoorAir:Mixer* object, which can only be at the outdoor temperature. Therefore, to account for corridor air being added to a zone, a *Coil:Heating:Electric* object is used to heat the outdoor air to a representative corridor temperature. This setpoint can be controlled to match the temperature of an adjacent zone, or any other temperature if needed. In reality, the theoretical heating that results from this object occurs in the other zones of the building since this air stream is meant to represent air flow through the corridor from adjacent zones that passes internally through the building. Therefore, the energy consumption of this object should be removed from the total building energy consumption to avoid double-counting the heating load.

Each of these objects combine to form the theoretical economizer system. Most of the inputs required to program this system in EnergyPlus are those needed to facilitate the connection between each of the objects. However, the determination of the volumetric flow rate limits for the *Controller:OutdoorAir* object is a critical aspect of this analysis methodology and requires detailed calculation. These details are presented in the next section.

Calculation of Outdoor Air Flow Rate Limits

In a high-rise MURB, the dominant air flow pathway through a suite has the corridor on one end, the suite in the middle, and the outdoor environment on the other end. Therefore, when analyzing the air flow rate along this flow pathway, there are two important analysis cases that must be considered. The first is when the window is closed and air flow occurs across the exterior envelope of the building when it is in its maximum air tightness configuration. The second case is when the window is open, and in this case it is assumed that the pressure drop across the exterior envelope is insignificant, resulting in the suite and outdoor pressure becoming equal. Schematic representations of these two cases are presented in Figure 3.

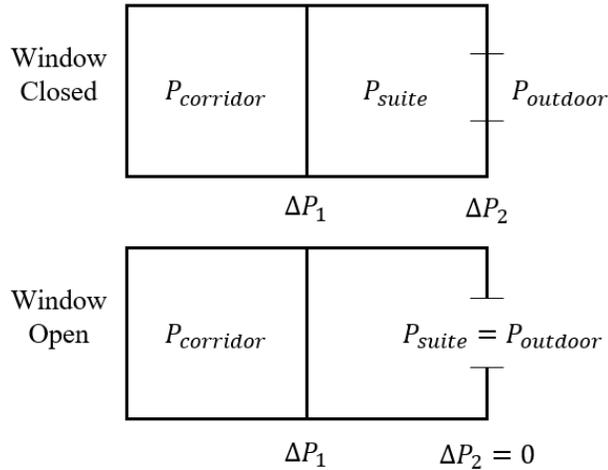


Figure 3: Pressure Boundary Diagram

As shown in Figure 3, in the “window closed” configuration there are pressure drops across the corridor-suite boundary and across the suite-outdoor boundary. In this configuration, it is assumed that the air flow across the two boundaries are equal. However, in the “window open” case there is only a pressure drop across the corridor-suite boundary since the exterior envelope pressure drop is assumed to be insignificant. This assumption implies that the outdoor air and suite air are the same air mass, and that air is theoretically flowing directly to the outdoors from the corridor. It is important to note that in both cases, the corridor pressure relative to the outdoor pressure is assumed to remain constant.

To analyze the volumetric flow through the system, the power law equation (ASTM, 2018) can be applied to the pressure boundaries, as shown in Equations (1) and (2).

$$Q = C_1(P_{corridor} - P_{suite})^{n_1} = C_1\Delta P_1^{n_1} \quad (1)$$

$$Q = C_2(P_{suite} - P_{outdoor})^{n_2} = C_2\Delta P_2^{n_2} \quad (2)$$

where Q is the volumetric flow rate of air, P_x is the gauge pressure in zone x , C_x is the flow coefficient for pressure boundary x , and n_x is the flow exponent for pressure boundary x . A sample application of this method follows.

One solution process, which was implemented in this study, is when the pressure of the suite is known in the “window closed” configuration, along with the air tightness characteristics of both pressure boundaries. In this case, the volumetric air flow through the system can be determined directly using Equation (2), yielding the minimum flow rate limit. This resulting air flow rate can then be used in Equation (1) to determine the corresponding corridor pressure at the given suite

pressure. Next, using this resulting corridor pressure, Equation (1) can then be used again while setting the suite pressure to the outdoor pressure (i.e. zero gauge pressure) to determine the maximum flow rate limit.

In the event that pressure monitoring is only carried out at a subset of locations in the building, such as at the top and bottom floors, the pressure differential between the suite and the outdoors at intermediate floors can be assumed to vary linearly from the bottom to the top of the building (ASHRAE, 2017). This variation method assumes that the leakage openings in pressure boundaries are distributed equally along the vertical axis of the building, and refinements to this assumption can be made if more detailed information is available.

Lastly, if long-term pressure measurements are not available to capture the effect of different outdoor temperatures, simplified modifications to the air flow limits can also be made to account for these changes. This modification is needed because the magnitude of the pressure generated by stack effect varies as a function of the temperature difference between the interior temperature and outdoor temperature (ASHRAE, 2017). To carry out this modification, the relationship shown in Equation (3) can be used.

$$\Delta P_{modified} = \Delta P_{measured} \times \frac{\Delta T_{modified}}{\Delta T_{measured}} \quad (3)$$

where $\Delta P_{modified}$ is the modified pressure differential, $\Delta P_{measured}$ is the measured pressure differential, $\Delta T_{modified}$ is the modified temperature differential, and $\Delta T_{measured}$ is the measured temperature differential that corresponds to $\Delta P_{measured}$. The result of Equation (3) can then be used with Equations (1) and (2) to determine the modified flow rate limits.

CASE STUDY

This section presents an overview of the case study building, along with the results from our field testing and calibration of the air flow model.

Building Overview

The case study building is a student family residence located in Toronto, Canada, built in 1968. This building was selected because it represents a typical post-war MURB in Toronto, where suites do not have individual temperature control and a central outdoor air reset control strategy is used to control the building heating system. The building includes pressurized corridor ventilation, constant-flow hydronic baseboards, and no central cooling. There are 20-stories with 304 suites. A rendering of the EnergyPlus model is shown in Figure 4.



Figure 4: Rendering of Case Study Building

This model included an individual thermal zone for each suite, along with an individual thermal zone for the corridor on each floor. Additional characteristics related to the building construction are presented in Table 1.

Table 1: Summary of Building Characteristics

PARAMETER	DESCRIPTION
Gross Floor Area	28,730 m ² (24,840 m ² above grade and 3,890 m ² below grade unconditioned garage)
Walls	Brick facade with concrete block backup wall (no insulation), gypsum board interior
Glazing	27% of wall area, double-glazed, low-emissivity with thermally-broken aluminum frames
Roof	Concrete slab with 50 mm polyurethane foam board, built-up roof membrane topped with ballast
Ventilation	Rooftop makeup air unit with pressurized corridors and door undercuts

Field Measurements and Derivation of Model Inputs

Field measurements were carried out to determine the airtightness of the corridor-suite pressure boundary and the suite-exterior pressure boundary. These air tightness measurements were carried out in a different building than the case study building, but the windows and corridor doors were similar. Additional field measurements in other buildings were also carried out, which showed that the air tightness characteristics of these components are similar in other similar buildings. Therefore, this usage of similar component data is acceptable for this particular modelling objective. A summary of the air flow characteristics that were derived is presented in Table 2.

Table 2: Pressure Boundary Flow Characteristics from Component-Level Testing

PRESSURE BOUNDARY	FLOW COEFFICIENT (L/s/Pa ⁿ)	FLOW EXPONENT
Corridor-Suite	6.4	0.583
Suite-Exterior	5.4	0.719

To determine the air tightness of the corridor-suite boundary, it was assumed that the major leakage pathway through this boundary was the suite entry door. This assumption was made because direct air flow measurements of this boundary were not possible and because there are large intentional gaps around the suite entry door to create an air flow pathway for ventilation air. In addition, measurements in similar buildings have also shown that the entry door is the dominant air flow pathway between the corridor and suite.

To determine the flow characteristics of the suite-outdoor boundary, the design operating conditions for the building makeup air unit (MAU) were used. These conditions assumed that the MAU generated a 10 Pa pressure differential between the suite and outdoors and delivered a total volumetric air flow rate of 26 L/s (55 CFM) to each suite. These conditions were derived from design specifications and measured air tightness data.

As part of the field-testing component, pressure monitoring was also carried out in the case study building during the month of January. This pressure monitoring showed that during the monitoring period, which had an average outdoor temperature of -5.9°C (21.4°F), typical in-suite pressures in the “windows closed” configuration at the top and bottom of the building were +26 Pa and -50 Pa, respectively. Therefore, at the top of the building there was exfiltration since the interior pressure was positive relative to the outdoor pressure, and at the bottom of the building there was infiltration. This result is expected given the low outdoor temperatures, resulting in stack effect that drove this air flow upwards through the building.

The results of these field measurements were then combined to calibrate the window modelling tool, and the results of this calibration are discussed next.

Determination of Flow Rate Limits

Using the measured and calculated field-testing results, the flow rate limits presented in Table 3 were determined. The limits in Table 3 correspond to those at the bottom and top of the building in January. The limits were then modified by varying the pressure linearly between the top and bottom of the building, and by modifying the flow rate as a function of the monthly average outdoor temperature and assuming a constant

Table 3: Summary of Air Flow Rates for Top and Bottom of Building

LOCATION IN BUILDING	WINDOW CONFIGURATION	ABSOLUTE PRESSURE DIFFERENTIAL BETWEEN SUITE AND EXTERIOR (Pa)	ABSOLUTE PRESSURE DIFFERENTIAL BETWEEN CORRIDOR AND SUITE (Pa)	RESULTING AIR FLOW RATE (L/S)
Bottom	Closed	50	93	90 (infiltration)
Bottom	Open	0	143	192 (infiltration)
Top	Closed	26	42	56 (exfiltration)
Top	Open	0	68	112 (exfiltration)

indoor temperature of 22°C using Equation (3). Using this process, the air flow limits were determined for each floor in the building and for each month of the year.

Case Study Simulation Results

The window modelling tool was then implemented as part of an annual simulation of the case study building. The monthly natural gas consumption was compared to measured utility data, which resulted in a coefficient of variation of the root mean square error (CVRMSE) of (NMBE) 7.0%, and a normalized mean bias error of 1.8%. These two parameters fall within the ASHRAE Guideline 14 model calibration requirements of 15% and 5%, respectively, verifying model accuracy (Landsberg et al., 2014). In addition, the model was run without window operability to verify that window operation impacts the model results. This simulation resulted in a CVRMSE of 18.4% and NMBE of 13.7%, further supporting the effectiveness of this modelling method.

Using this model, a comparison was carried out between the economizer modelling technique and the *WindandStackOpenArea* modelling technique. This comparison was carried out by first running the calibrated simulation using the economizer window model, changing the window model in a single suite to the *WindandStackOpenArea*, and then re-running the simulation. The interior temperature and window volumetric air flow rate results from both simulations for this suite over a 48-hour period in January are presented in Figure 5 and Figure 6, respectively.

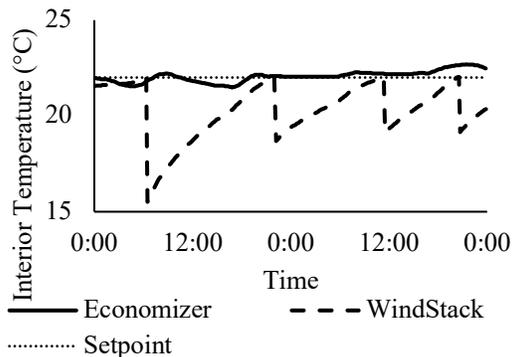


Figure 5: Plot of Comparative Temperature Results

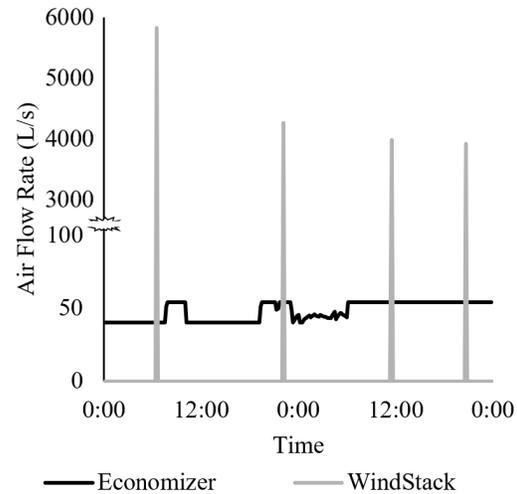


Figure 6: Plot of Comparative Window Volumetric Air Flow Results

As shown in Figure 5, the economizer modelling technique results in temperature variations of less than 1°C when the window air flow rate is increased. This consistency is in contrast to the temperature changes on the order of 5°C exhibited by the *WindandStackOpenArea* technique over a single time step. However, it should be reiterated that the economizer technique does not currently account for human behavioural aspects and assumes that occupants are consistently adjusting the window opening to achieve a pre-defined set point, increasing temperature uniformity. In the future, this economizer modeling concept needs to be integrated with established models of occupant-based window opening and closing behavior to be representative of real building performance.

Lastly, as shown in Figure 6 (note discontinuity in y-axis), the window air flow rates are also more consistent when using the economizer as compared to the *WindandStack* object, which yields a more sporadic flow rate due to the wind-induced air flow calculation method that was previously discussed. While the flow rates from the *WindandStackOpenArea* model are much higher and more sporadic than the economizer, the average air flow rates for both models over the 48-hour sample period are

similar, yielding 1.4 and 1.5 ACH for the *WindandStack* and economizer models, respectively. These average results align well with tracer gas field measurements that were carried out in a similar building, with measurements ranging from 1.15 to 1.56 ACH, and support that both models can capture overall air flow trends. However, the consistent air flow results from the economizer yield more stable and realistic interior temperatures, while still allowing for the effect of operable windows to be captured, improving the simulation.

CONCLUSION

In conclusion, existing tools in EnergyPlus have limitations when modelling operable window air flow to provide space cooling. This study focused on the development of an alternative modelling method, where the window was modelled as a theoretical economizer. This technique offers improved flexibility compared to the *WindandStackOpenArea* object and is more practical to implement than an *AirflowNetwork*. A case study building was simulated using this modelling technique, which yielded a more realistic representation of the effect of window opening on building performance. Future work will investigate improving the control of this object to allow for better representation of occupant behaviour.

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NOMENCLATURE

SYMBOL	EXPRESSION	UNIT (SI [IP])
Q	Volumetric Flow Rate	L/s [CFM]
C	Flow Coefficient	$L/s/Pa^n$ [CFM/ Pa^n]
n	Flow Exponent	<i>dimensionless</i>
P	Pressure	Pa
ΔP	Pressure Differential	Pa
ΔT	Temperature Difference	$^{\circ}C$ [$^{\circ}F$]

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