IOP Conf. Series: Materials Science and Engineering **609** (2019) 042102 doi:10.1088/1757-899X/609/4/042102

Building Energy and IAQ improvement by Coupled Model

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Abstract. The building performances are related to Energy Efficiency and Indoor Air Quality (IAQ). Modeling is one of the best accurate tools for measuring the building performance. Nowadays, Energy Efficiency and IAQ are modeled individually for buildings. Improvement strategies in both areas are analyzed separately. The fundamental problem in Energy and IAQ modeling is related to interaction to each other. This problem makes the modeling results unrealistic to the building performance solutions. To avoid this problem, in this current research, Energy and IAQ models are coupled simultaneously as a new co-simulation method. EnergyPlus and CONTAM are used as Energy and IAQ models, respectively. With the co-simulation method, these two models are coupled together. The method is based on the exchange of control variables between both models dynamically and simultaneously. As a result, the exchanges of temperature and air flow variables are corrected. The verification of the new model is based on the comparison of the simulation and analytical results of temperature and air flow variables. In the next step, this new coupling-co-simulation method for a townhouse building is done in two cases: a leaky and a tight building envelopes. Both cases are compared in two types of ventilation systems: infiltration only, and exhaust only. At this point, the simulated air change rates, gas energy use, and particles concentrations are compared for each case. Finally, the necessity of the accuracy of this new method is concluded.

1. Introduction

Energy-efficient building design is one of the most important issues in the field of building science. Many discussions on building energy efficiency neglect their potential impacts on IAQ [1]. Limiting the implementation of some energy efficiency technologies and considering their impacts on IAQ shows that current energy design and analysis tools are limited in their capability to model correctly the airflow and IAQ in buildings [2]. Adams et al. [3] used a coupled airflow–thermal model to show that the use of a heat recovery ventilation resulted in 20% energy savings and reduced contaminant levels. Some energy simulation software tools can simulate airflow using multizone airflow models, but the air flow calculation capabilities are often limited and can be difficult to be used [4]. Almost all previous studies have focused on only one aspect, either the building energy conservation or the IAQ [5]. The building energy conservation and IAQ are the two most important themes of an ecological building, both of which cover multidisciplinary issues and, interact with each other [6]. Energy models are used as well as precision tools for building integrated dynamic optimization by using the coupling method for the load and HVAC systems [7, 8]. Modern buildings and their heating, ventilation and air-conditioning systems are now needed not only to improve energy efficiency, but also to meet the growing demand for better comfort performance [9]. In addition, poor indoor comfort has direct effects on user productivity and indirect effects on building energy efficiency [10]. EnergyPlus is a complete energy simulation program for a multi-zone thermal balance calculation method [11]. Chen et al. used EnergyPlus to simulate the heat, air, and moisture balances and used CHAMPS-Multizone to simulate IAQ [12]. Co-simulation has been used to analyze the interaction between IAQ and energy efficiency [12, 13]. Dols et al used the co-simulation method for the first time between EnergyPlus and CONTAM

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[13]. CONTAM predict airflow based on the contaminating concentrations generated in the whole multizone buildings. CONTAM in order to be able to perform IAQ calculations, it requires indoor temperatures as input data.The air flow temperature is assumed to be in the set-point of the thermostat for IAQ calculation in CONTAM and this is the limitations of the IAQ calculation by using the single models [14]. In this current research, EnergyPlus and CONTAM are used separately to improve energy consumption and IAQ for the leaky and tight buildings with different ventilations. In the next step, using a co-simulation method by development of the coupled EnergyPlus-CONTAM model. The results of each of single and coupled models are analyzed for three scenarios.

2. Methodology

This research consists of three main parts. In the first part, how to develop the model using the co-simulation method for coupling between EnergyPlus and CONTAM is investigated. In the second part, the verification method for developed model is used based on the available methods. At the final part, application of the model at first by using EnergyPlus and CONTAM programs separately and then with co-simulation method, are analyzed. By using the single and coupled models, air change rates, indoor particles concentrations and gas consumption for a case study townhouse in different scenarios are simulated and then compared.

2.1 Coupling method between EnergyPlus and CONTAM

The coupling method is performed based on the energy and mass balances equations. EnergyPlus and CONTAM calculates the energy and mass balances, respectively, according to the Figure 1.

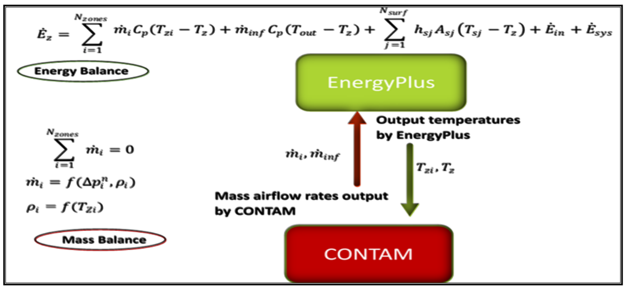

Figure 1. Coupling method mechanism for EnergyPlus and CONTAM models.

2.2 Co-simulation approach between EnergyPlus and CONTAM

The co-simulation method, between EnergyPlus and CONTAM, is illustrated in Figure 2. The format of input data to CONTAM is PRJ file (Project file). In addition, the input data to EnergyPlus is formatted as an IDF file (Input data file). The Contam3DExporter tool also can convert the PRJ file into two types of VEF file and XML file formats. These files are exchanged during co-simulation between both Contam X and EnergyPlus models as shown in Figure 2. These data and control variables are exchanged between the two models by ContamFMU (Functional Mock-up Unit). RST file is simulated for 24 hours in order to synchronize the exchange times at specific time steps.

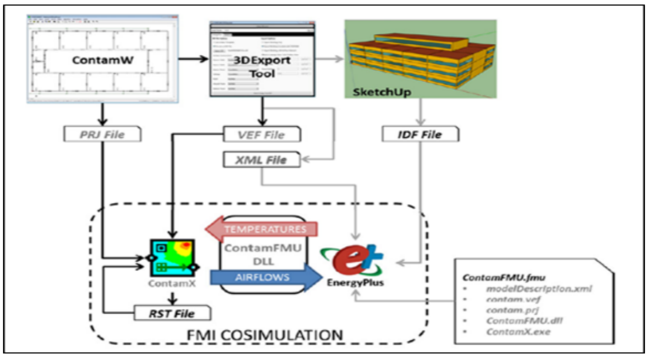

Figure 2. Co-simulation approach for CONTAM and EnergyPlus [13].

2.3 Verification of coupling method for the developed EnergyPlus-CONTAM model

The model is validated using the Dols et al. verification method [13]. They used the multizone case MZ320 [15] as a test case to verify the coupled Energy-CONTAM model. In this current research, Dols et al. [13] verification method has been used with some changes. The new test case MZ320, with changes are defined according to Figure 3 for zones of A, B and C.

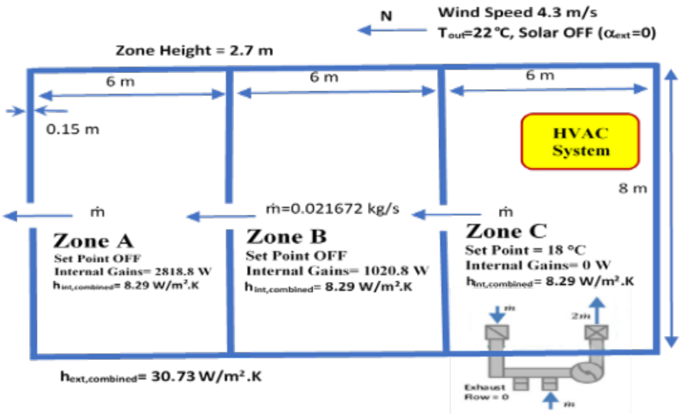

Figure 3. New test case MZ320 for verification of co-simulation method

This verification is done in two steps. In the first step, analytical heat balance calculations are performed for the new test case MZ320 based on Equations (1,2 and 3) for the three zones, A, B and C. In these equations, TA, TB and $\dot{Q}$ are unknown.

$$\dot{Q}_A = 0 = \dot{Q}_{int,A} - U_{in}A_{com}(T_A - T_B) - U_{ex}A_{ext,A}(T_A - T_{out}) - \dot{m}C_p(T_A - T_B) \quad (1)$$

$$\dot{Q}_B = 0 = \dot{Q}_{int,B} - U_{in}A_{com}(T_B - T_A) - U_{in}A_{com}(T_B - T_C) - U_{ex}A_{ext,B}(T_B - T_{out}) - \dot{m}C_p(T_B - T_C) \quad (2)$$

$$\dot{Q}_C = \dot{Q}_{int,C} - U_{in}A_{com}(T_C - T_B) - U_{ex}A_{ext,C}(T_A - T_{out}) - \dot{m}C_p(T_A - T_B) \quad (3)$$

By solving these three Equations (1,2 and 3), the values for TA, TB and $\dot{Q}_C$ are 33.65 °C, 26.54 and 1361.23 W, respectively. In the second step, the new test case MZ320 is modeled by using the co-simulation method. In this method, calculations of the heat balance between zones are done by EnergyPlus. The calculation of the mass balance between zones is done by Contam X. In the co-simulation method, the MZ320 model as PRJ file is inserted into the Contam X. Three files were produced by the CONTAM3D exporter. One of them as an IDF file is used for EnergyPlus. Two other files, which include the VEF and XML files, are taken as inputs in to the FMU co-simulation. ContamX calculate the zone mass balance. In zone C, the air handling system is defined with a supply airflow rate of 0.043 (kg/s). Also, an exhaust fan with an airflow rate of 0.021672 (kg/s) is considered. The HVAC AirLoop EnergyPlus heat balance calculation has been selected as a CAV-type HVAC system. The thermal conduction and convection coefficients of the exterior and interior walls and other energy-related components and properties are defined in EnergyPlus. The results of the simulation of TA, TB and $\dot{Q}_C$ using the EnergyPlus-CONTAM co-simulation method, have been compared with the results of the analytical solutions of Equations (1, 2 and 3) in Table 1.

Table 1. The results of analytical and co-simulation calculations for the new case MZ320.

	Results	*TA(°C)*	*TB(°C)*	*TC(°C)*	*Cooling Load in Zone C (W)*
1	Analitical Test Case	33.650	26.540	18.00	1361.228
2	Co-Simulation Test Case	33.656	26.544	18.00	1361.233

In this comparison, the difference between simulated and analytical values is less than 0.006. Regarding these results, it can be concluded that the co-simulation model has been verified and checked.

2.4 Description of the Case study's model

In this current research, a three-storey townhouse in the city of Montreal is used for simulation. This house comprises four levels. The basement includes gas furnace, gas hot water heater and dryer, all of which are externally ventilated. The area of basement is 24 m^2 and the volume is 72m^3. The second level includes a living room, kitchen, bathroom, hall closet and a fireplace in the living room. The area of this level is $35m^2$ and the volume is $105m^3$. Third level includes master bedroom, master bedroom closet, master bathroom, bathroom, hall, two bedrooms and a bedroom closet. The area of this level is $37m^2$ and the total volume of this level is 111 m^3. The last level is the attic with area 13 m^2 and the volume is 50 m^3. The initial input data of the EnergyPlus and CONTAM models are : dimensions and plans of the house, shielding near the building type, size of zones, orientation, geographic location, ambient temperature, envelope material and insulation, weather data files, outdoor particles data, indoor particle sources, cooking source, smoking source, envelope leakage rate, filtration, minimum efficiency reporting value (MERV), wind pressure coefficient and direction, number of occupants, flow paths (HVAC ducts, doors, windows, cracks, etc), ventilation type and other related mechanical - construction systems data. The EnergyPlus calculates the amount of energy consumptions in the whole building based on the energy balance method between building zones and boundary conditions, as well as between interzones. Systems airflow rate has an important application in the energy transfer between the energy sources and the building multizone or interzones. Airflow rate systems include infiltration and interzone airflow. HVAC systems, as a source of energy in the building boundary condition, uses infiltration for the displacement of energy and zone air temperature. The CONTAM can calculate the air flow rate system based on the contaminant concentration and other IAQ characteristics, such as occupant exposure for the building multizone and interzone.

3. Results

The results of this research include three steps: 1- separate energy and IAQ simulation for the baseline scenario as a reference step, 2- separate energy and IAQ simulation for two scenarios, and, 3- co-simulation of energy-IAQ for improvement of the building performance for scenario 3. Three scenarios are defined for this case study. Each scenario is compared to the baseline scenario (Table 2).

Table 2. Comparison of 3 scenarios with the baseline

	Cases	*Tightening*	*Exhaust Fan*	*Filter Upgrading*
1	Baseline	no	no	no
2	Scenario 1	yes	no	no
3	Scenario 2	no	yes	no
4	Scenario 3	yes	yes	yes

According to the Table 2, the scenarios are defined based on tightening, exhaust fan and filter upgrading.

3.1 Simulation results of the base case scenario

Simulations on the base case include air change rates, indoor particles concentrations and gas energy consumptions. The results of this simulation are reported based on the third week of each season for all energy and IAQ parameters. For this base case, the air handling system (AHS) is operated with a total volumetric airflow of 0.40 (m^3/s). Also, in this AHS, the MERV 4 furnace filter is used in one single pass. The number of residents is 5 people. The sizes of the indoor and outdoor particles for P1, P2, P3, P4 and P5, respectively, are in the range of 0.3 µm to 0.5 µm, 0.5 µm to 1.0 µm, 1.0 µm to 2.5 µm, 2.5 µm to 5.0 µm, 5.0 µm to 10 µm. Indoor particles generation rates were used based on the Howaed-Reed et al. measurements [16]. Outdoor particle concentrations, measurements performed by Smargiassi et al. in 2005 in four sites in 7 weeks in an urban residential area of Montreal [17]. The results for the air change rates, indoor particles concentrations simulation by CONTAM and gas energy consumptions simulation by EnergyPlus in each season are shown in Figures 4, 5 and 6.

3.2 Simulation results of the scenario 1 to 3 cases

In scenario 1, to reduce the residential energy loss, the exterior envelope is improved to tight envelope. All exterior envelope leakage area elements are reduced to 45% of the base case. In scenario 2, to reduce indoor particles concentrations, the type of ventilation is improved from infiltration only to exhaust fan only. For this purpose, the exhaust fan with 50 (L/S) air flow rate is used. In scenario 3, the combination of positive effects of tightening and exhaust fan ventilation on the two previous scenarios as well as filter upgrading to MERV 12 has been used to reduce indoor particle concentration and gas energy consumption both together. The seasonal simulated results in minimum, average and maximum values of air change rates, indoor particles (P5) and gas energy consumptions for the scenarios 1 to 3 compared with the baseline case are shown in Figures 4, 5 and 6, respectively.

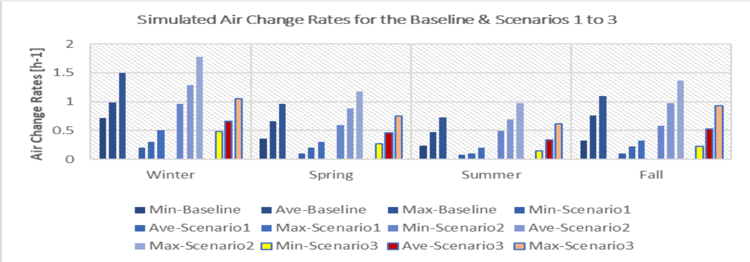

Figure 4. Air changes rates simulations results for basement and scenarios 1 to 3.

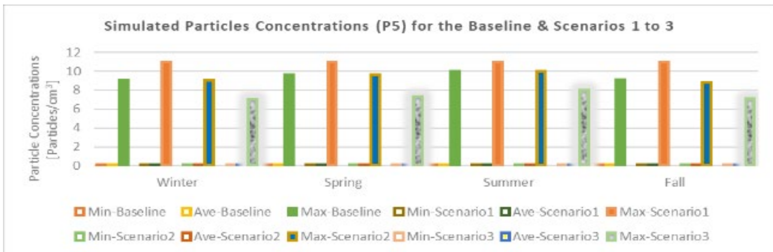

Figure 5. Indoor particles Concentrations (P5) simulations results for basement and scenarios 1 to 3.

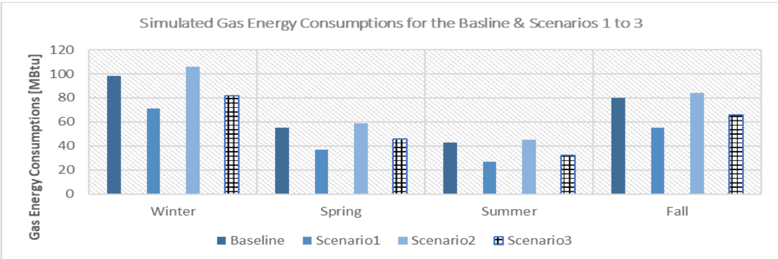

Figure 6. Gas energy consumption simulations results for basement and scenarios 1 to 3.

In Table 3, the percentage of average annual values of simulated air change rates, indoor particles concentrations (P5) and gas energy consumptions for scenarios 1, 2 and 3, are compared with the baseline case.

Table 3. Comparison of percentage IAQ and energy parameters for 3 scenarios with the baseline.

Average annual parameters relative to baseline	*Scenario 1 (%)*	*Scenario 2 (%)*	*Scenario 3 (%)*
Airchange rates	70 ↓	33.2 ↑	26 ↓
Indoor Particles Concentrations (P5)	16.5 ↑	0.85 ↓	22.07↓
Gas Energy Consumptions	31.1 ↓	6.5 ↑	18.4 ↓

4. Discussion

The main objective of this research is to develop a combination of energy and IAQ models to increase the accuracy and improve the performance of building. For this purpose, the coupled EnergyPlus-CONTAM model was developed. The co-simulation method for exchanging control variables of temperatures and airflow rates between EnergyPlus and CONTAM is used to solve the simultaneous energy balance and mass balance. To highlight the limitations of single model compared to the coupled model, simulation results are compared to each other for energy and IAQ improvement measures for a whole townhouse with three-story located in the city of Montreal. The impact of the airtightness, exhaust fan and upgrading of filter, measures are evaluated in the context in improving energy consumption and IAQ (see Figures 4, 5 and 6). In scenario 1, the airtightness has improved the energy consumptions, but has had a negative impact on air exchange rates and IAQ. Even in scenario 2, despite the increase in the air change rates flow and high energy consumption, the exhaust fan does not make acceptable improvements on IAQ. This problem is due to the simulation’s limitations of the single EnergyPlus and

CONTAM programs, which are analyzed in scenarios 1 and 2. In order to improve both the energy and IAQ, scenario 3 is defined for the coupled EnergyPlus-CONTAM model. According to Table 2, three performances strategies are used for this scenario 3. In scenario 3, the results of all three simulated air change rates, indoor particles concentration (P5) and gas energy consumptions due to the exchange of parameters related to the mass and energy balances are related to each other. Accordingly, the value of airtightness and the type and capacity of ventilation can be chosen so that both energy and IAQ measures can be improved together.

Conclusion
As a result of modifying the scenario 3, the exterior envelope airtightness status is selected to be 42% higher than the base case. Also, the air flow rate for the exhaust fan, 26 (L/s) is selected as continuous ventilation. Particle air filter with higher efficiency (MERV 12) is used to further reduce indoor particles concentration. Summary of the result analysis, the simulated average parameters, are shown in annually format in Table 3. According to the Table 3, scenario 3 by co-simulation is better than other scenarios 1 and 2 for improving energy and IAQ together and necessity of using this new method is concluded.

References
[1] Kusiak A. Artificial intelligence : implications for CIM. New York: Springer-Verlag; 1988. 527 p. p.
[2] Ng LC, Musser A, Persily AK, Emmerich SJ. Multizone airflow models for calculating infiltration rates in commercial reference buildings. Energy and Buildings. 2013;58:11-8.
[3] Adams E. Simulations of IAQ and comfort in multizone buildings. Indoor Air. 1993;93:533-8.
[4] Ng LC, Quiles NO, Dols WS, Emmerich SJ. Weather correlations to calculate infiltration rates for US commercial building energy models. Building and environment. 2018;127:47-57.
[5] Bai Z, Wang Z, Zhu T, Zhang JJ. Developing indoor air quality related standards in China. Journal of Asian Architecture and Building Engineering. 2003;2(1):55-60.
[6] Zhang J, Bai Z, Chang VWC, Ding X. Balancing BEC and IAQ in civil buildings during rapid urbanization in China: Regulation, interplay and collaboration. Energy Policy. 2011;39(10):5778-90.
[7] Heibati SM, Atabi F, Khalajiassadi M, Emamzadeh A. Integrated dynamic modeling for energy optimization in the building: Part 1: The development of the model. Journal of Building Physics. 2013;37(1):28-54.
[8] Heibati SM, Atabi F. Integrated dynamic modeling for energy optimization in the building: Part 2: An application of the model to analysis of XYZ building. Journal of Building Physics. 2013;37(2):153-69.
[9] Neto AH, Fiorelli FAS. Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. Energy and buildings. 2008;40(12):2169-76.
[10] Kolokotsa D, Tsiavos D, Stavrakakis G, Kalaitzakis K, Antonidakis E. Advanced fuzzy logic controllers design and evaluation for buildings' occupants thermal–visual comfort and indoor air quality satisfaction. Energy and buildings. 2001;33(6):531-43.
[11] Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy and buildings. 2001;33(4):319-31.
[12] Chen Y, Gu L, Zhang J, editors. EnergyPlus and CHAMPS-Multizone co-simulation for energy and indoor air quality analysis. Building Simulation; 2015: Springer.
[13] Dols WS, Emmerich SJ, Polidoro BJ, editors. Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation. Building simulation; 2016: Springer.
[14] Dols WS, Underhill LJ. Cross-platform, Public Domain Simulation Tools for Performing Parametric IAQ and Energy Analysis: National Institute of Standards and Technology; 2018.
[15] Neymark J, Judkoff R, Beausoleil-Morrison I, Ben-Nakhi A, Crowley M, Deru M, et al. International energy agency building energy simulation test and diagnostic method (IEA BESTEST): in-depth diagnostic cases for ground coupled heat transfer related to slab-on-grade construction. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2008.
[16] Wallace LA, Emmerich SJ, Howard-Reed C. Source strengths of ultrafine and fine particles due to cooking with a gas stove. Environmental Science & Technology. 2004;38(8):2304-11.
[17] Smargiassi A, Baldwin M, Pilger C, Dugandzic R, Brauer M. Small-scale spatial variability of particle concentrations and traffic levels in Montreal: a pilot study. Science of the Total Environment. 2005;338(3):243-51.