# DEVELOPMENT OF BASELINE BUILDING ENERGY MODELS FOR THE ADVANCED OCCUPANT-CENTRIC BUILDING CONTROL RESEARCH IN THE VARIOUS U.S. CLIMATES

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## ABSTRACT

This study refines the existing large and medium office models from the U.S. DOE Commercial Prototype Building Models (CPBM) to accommodate the purpose of occupant-centric control (OCC) implementation and evaluation. Firstly, a detailed rezoning plan was created to add the zoning diversity (e.g., closed office, open office, conference room) to the original medium and large office models in the CPBM. Next, a unique set of dynamic occupancy schedules were generated using a statistical tool for each room to represent the occupancy variation. Then, two OCC cases were generated utilizing the occupancy presence sensing and occupant counting technologies. Finally, the refined models were extended to different versions of ASHRAE standards (e.g., ASHRAE Standard 90.1-2004, 2007 and 2010) and various U.S. climate zones following the code requirement. The simulation results suggested that the presented OCCs could achieve huge energy savings for the HVAC system, especially in cold climates.

## INTRODUCTION

### Occupant-centric control

The Americans spend 90% of their time indoors on average (US Environmental Protection Agency 1989). Despite the huge amount of energy consumed by the buildings for space heating and cooling, there is an ongoing necessity to recognize and consider the growing needs and comfort expectations of the occupants in the built environment in building design and operation. On the one hand, the occupant's health, well-being, and productivity are highly related to the indoor environment and indoor air quality (IAQ) (Hensen and Lamberts 2012). On the other hand, building energy consumption is highly influenced by the presence of occupants and their interactions with the building system (Hong et al. 2016).

Occupant-centric control (OCC), of which the definition may vary from case to case (Naylor et al. 2018; Park et al. 2019), is attracting significant research interests from both the academia and industry in this context. This is largely due to its ability to address the contradiction between the needs of reducing building energy consumption and maintaining the occupant's thermal comfort. Naylor et al. (2018) summarized that the OCCs can generally be categorized into four groups, i.e., the real-time reactive control to the occupancy presence, the personalized control to the individual preference, the control catered to the individual behaviors, and the predictive control based on the occupancy presence/behavior prediction models. Park et al. (2019) further simplified the classification of OCCs into two sub-categories: the occupancy-based control which adjusts the system operation merely based on the presence/absence of the occupants; and the behavior-based control which utilizes the human-building interactions in conjunction with various environmental measurements to determine the system operation.

The huge energy savings potential of OCC has been demonstrated by multiple case studies from the perspectives of both computer simulation and field implementation. For instance, Zhang et al. (2013) investigated the use of occupancy presence sensor and occupant counting sensor in the building lighting control and the variable-air-volume (VAV) system terminal box supply airflow rate reset. The nation-wide analysis results suggested that the proposed OCC could save as much as over 19% of the total building energy consumption in the representative cities with cold climates, e.g., Duluth, MN, Burlington, VT, and Salem, OR (Zhang et al. 2013a). Besides, Winkler et al. (2016)

developed a control platform that adjusts the heating, ventilation, and air-conditioning (HVAC) system using the occupant votes and implemented this platform in an on-site experimental in three buildings during a 40-week study. The results indicated that this platform could improve user satisfaction from 33.9% to 93.3% and reduce as much as 19% energy consumption (Winkler et al. 2016).

**Technical gap**

The last decades have seen growing prosperity in OCC research and application. On the one hand, manufacturers keep launching new smart residential thermostat products which are capable of occupancy sensing and various learning abilities. On the other hand, the new OCC algorithms and logics continue to be brought up for achieving better control. However, the technical gaps still exist, which hinders a deeper understanding and demonstration of the OCC.

The first gap faced with the building energy modeler is that the field study is not easy to implement in practice due to various factors (Park et al. 2019). This is confirmed in a review article by Park et al. (2018), that only 42 out of the 120 reviewed OCC case studies included a field implementation while others only featured either a conceptual OCC or simulation-based/chamber study for OCC verification. And within the 42 field case studies, most of them were suffering from issues like the number of control zones is too few, the experimental span is too short, or limited building type(Park et al. 2019). As a consequence, the authors recommended a simulation analysis prior to field implementation.

While the simulation-based study could avoid the barriers of looking for an appropriate building candidate and the high initial costs for sensors and labor, the second technical gap still exists: there lacks a validated baseline model for the performance comparison across various OCCs. While the OCC is mainly focused on the building occupants, and the energy savings potential is mainly demonstrated from the variations in occupancy schedules and occupant behaviors, the various parameters during the development of the baseline model could also pose positive or negative influences to the energy-saving ratios, for instance, the selection of the building envelopes for different climates, the action of the energy recovery unit (ERV). Naylor et al. (2018) reviewed some simulation-based OCC studies and concluded that the differences in occupancy schedules and occupant behaviors in building energy simulation could result in significant variations in energy savings.

There have been a number of building codes and standards in different countries and regions, with each standard having multiple versions and addendums. For example, the ANSI/ASHRAE/IES Standard 90.1-Energy Standard for Buildings Except Low-Rise Residential Buildings is updated every three years. In each update, the changes were made in regard to the building envelope requirement, mechanical equipment efficiencies, and HVAC system control logic, etc. Considering that there lacks a standardized building energy model, the simulation community needs to develop a set of baseline building energy models which are code-compliant and versatile for various OCC application.

**Commercial Prototype Building Models**

Commercial Prototype Building Models (CPBM) were developed and are continuously maintained by Pacific Northwest National Laboratory (PNNL), in support of the U.S. Department of Energy (DOE) Building Energy Codes Program (Halverson et al. 2014; Thornton et al. 2011). These models cover 16 building types, 17 IECC climate zones (IEC 2012), and multiple versions of ASHRAE Standard 90.1 and IECC Standard. These models represent the majority of the commercial building stock and mid-rise to high-rise buildings and cover 80% of the new commercial constructions in the U.S. (Goel et al. 2014).

Having been reviewed by building industry experts on ASHRAE 90.1 Standing Standard Project Committee, CPBM have been widely used in various simulation-based studies as the baseline model, e.g. (Pang and O'Neill 2018). However, there are some inherent limititions for the current version of CPBM regarding its application for the OCC research, e.g., the static and homogeneous occupancy schedules, and the relatively simplified zoning plan in a few building types.

**Objective**

This study aims to develop a set of baseline building energy models. The proposed work is based on the medium office and large office buildings in the CPBM. To accommodate the implementation of OCC, firstly, a detailed rezoning plan was created to add the zoning diversity (e.g., closed office, open office, conference room) to the original medium and large office building models in the CPBM. Then, two OCC cases were generated utilizing the occupancy presence sensing and occupant counting technologies. Next, a unique set of dynamic occupancy schedules were generated using a statistical tool for each room to represent the occupancy variation. Then, the refined models were extended to different versions of ASHRAE standards (e.g., ASHRAE Standard 90.1-2004, 2007, and 2010) and various U.S. climate zones following the code requirement. A simple energy usage comparison between the original CPBMs and the newly refined models is then conducted to validate the proposed work. Finally, conclusions and future work are summarized.

## METHODOLOGY

This section discusses the development of the proposed OCC baseline models.

### Existing CPBM models

As has been mentioned previously, the proposed work is based on the medium office and large office models in the CPBM. Some enhancements were made to accommodate the models to OCC application, but the model basic geometries and HVAC system configurations were retained. The basic information about the two models was listed in Table 1 and Table 2. Please be noted that the building envelop is not included since it tends to vary with the building code and climate zone. The specification of the building envelop and mechanical equipment efficiency is elaborated in the following part.

*Table 1 The basic information of the medium office*

| ITEM | DESCRIPTION |
|---|---|
| Area | 4,980 $m^2$ (49.9 m * 33.2 m * 3 floors) |
| Window fraction | 33% |
| Heating | Gas furnace inside the packaged air conditioning unit |
| Cooling | Packaged air conditioning unit |
| Air terminal | VAV terminal box with damper and electric reheating coil |

*Table 2 The basic information of large office*

| ITEM | DESCRIPTION |
|---|---|
| Area | 46,321 $m^2$ (73.2 m*48.8 m*13 floors) |
| Window fraction | 40% of above-grade gross walls |
| Heating | One gas-fired boiler |
| Cooling | Water-source DX cooling coil with fluid cooler for data center and IT closets;<br>Two water-cooled centrifugal chillers for common spaces |
| Air terminal | VAV terminal box with damper and hot-water reheating coil |
| Cooling tower | Two-speed fluid-cooler for data center and IT closets; Open cooling tower with two-speed fans for common spaces |

### Detailed zoning plan

Occupant presence and movement in the buildings have significant influences on the building energy consumptions and the performances of the OCCs (Chen et al. 2018). This influence is especially strong when the OCCs are implemented, e.g., the temperature setback control during the occupied standby mode, the demand-controlled ventilation (DCV) in densely occupied zones, etc.

The zoning plans of the original medium office and the large office in CPBM are coarse and lacking in detail, as illustrated in Figure 1. Each floor is just divided into four perimeter zones and one core zone to facilitate the load calculation. This makes it hard to capture the zone-level occupancy fluctuation due to occupant movement, e.g., attending conference. To simulate occupants' movement, the original CPBM need some enhancements.

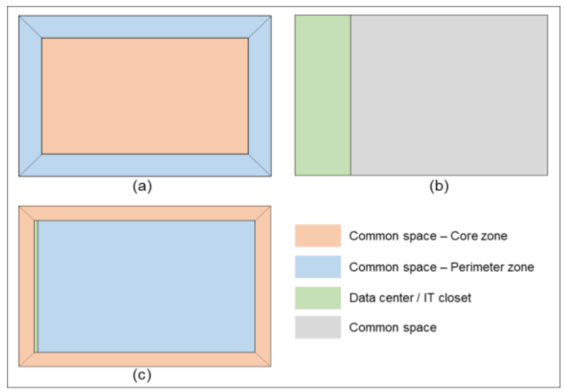


*Figure 1 The zoning plans of (a) medium office; (b) large office – basement; and (c) large office – other floors*

Following the work of Oak Ridge National Laboratory (ORNL) on updated OpenStudio Office Prototype Models (Im et al. 2019), a new zoning plan was created for the medium office and large office in CPBM respectively. As shown in Figure 2 and Figure 3, these new zoning plans divide the original large zones into multiple smaller zones, with each zone representing a specific space type (e.g., open office, conference room, enclosed office, etc.). This new zoning plan is suitable for simulating the various occupant behaviors in different space types and situations. Besides, some modifications were made on the basis of the ORNL's work to divide further the original large enclosed offices, which could contain more than two people into smaller ones, which only holds two occupants each. As shown in Figure 4, this modification can capture the energy savings potential of small individual offices.

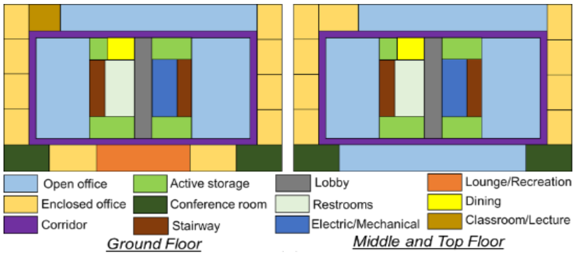


*Figure 2 The zoning plan of the refined medium office model after zoning enhancement*

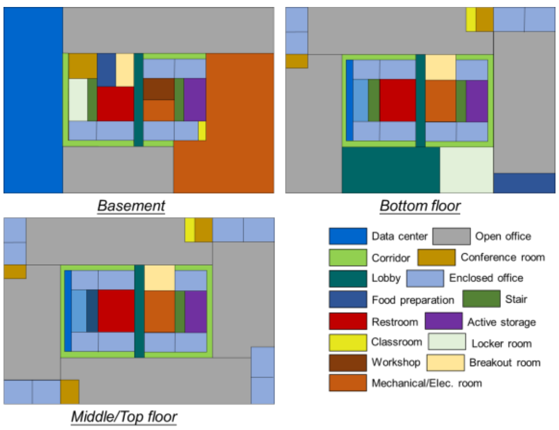


*Figure 3 The zoning plan of the refined large office model after zoning enhancement*

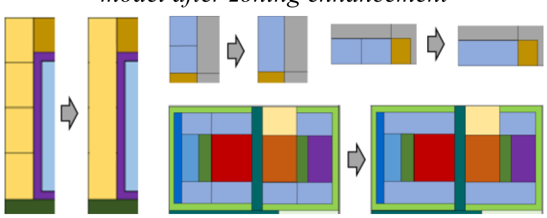

*Figure 4 The refinement of the original enclosed offices in ORNL's work (Im and New 2018)*

Consequent changes in the HVAC and mechanical system, such as re-specifying the lighting power density (LPD) and equipment power density (EPD), adding thermostat objects and VAV terminal objects to the newly-added zones and modifying the air loop and chiller/boiler loop were made following the rezoning work. The details are not elaborated here.

**Dynamic occupancy schedules**

The original CPBM do not consider the occupant's random movement among the zones, as well as the consequent variations in the zone-level occupancy. Hence, the occupancy schedules are static and homogeneous. To overcome this issue, this study generated a set of dynamic occupancy schedules to bring random variations to the occupancy schedules.

The Occupancy Simulator developed by Lawrence Berkeley National Laboratory (Chen et al. 2018) was used to generate the dynamic and stochastic occupancy schedules. This tool incorporates several validated occupant behavior models and is able to create building-level and space-level occupancy schedules as well as the movement of an individual person by pre-defined occupant types and space types.

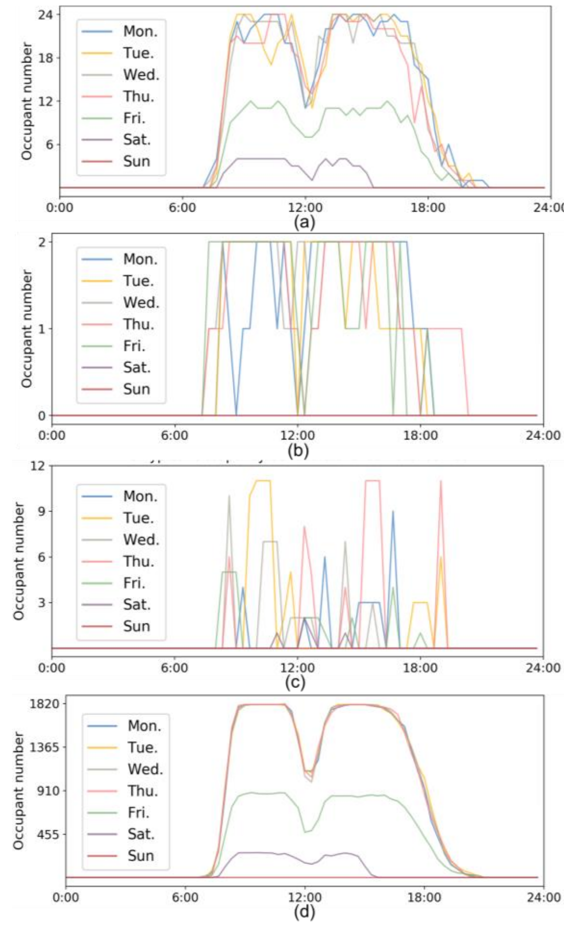


*Figure 5 The sample occupancy schedules of (a) a typical open office; (b) a typical enclosed office; (c) a typical conference room; and (d) the whole building for the large office model*

In this study, the baseline occupancy density was specified following ASHRAE Standard 62.1 – 2016 (ASHRAE 2016). The arrival and departure time, the weekly variations in attendance rate, and the meeting events were specified based on engineering judgments. Some of the assumptions were summarized in Table 3.

*Table 3 The assumptions for generating occupancy schedules*

| DAY | ASSUMPTION |
|---|---|
| Mon. – Thu. | HVAC operation: 7 AM – 9 PM;<br>All the employees will go to work. |

| | |
|---|---|
| Fri. | HVAC operation: 7 AM – 9 PM;<br>Only half of the employees will go to work. |
| Sat. | HVAC operation: 7 AM – 4 PM;<br>Only 20% of the employees will go to work. |
| Sun. & Holiday | HVAC system always off<br>None of the employees will go to work. |
| Night cycle | The HVAC system will be kicked on when there is a heating/cooling demand during the system-off period. |

The occupancy schedule was generated on a weekly basis, i.e., a weekly schedule was iterated to represent the whole year. The schedule varies for different zones to fully demonstrate the stochastic nature in occupant behavior. Some sample occupancy schedules of representative zones were presented in Figure 5 to illustrate the trends and variations of the occupancy presence in the proposed models. As noted by Hong et al. (2016), this dynamic variation helps demonstrate the energy savings potential of the OCC. However, it should be noted that the dynamic occupancy schedules used in this study were created based on the engineering judgements; hence any change made to the assumptions in Table 3 may impact on the OCC energy-saving performance.

## VAV system control logic

### *Sensing technology*

The up-to-date control algorithms from ASHRAE Standard 62.1 – 2016 Ventilation for Acceptable Indoor Air Quality (ASHRAE 2016), Addendum G to ASHRAE Standard 90.1 -2016 (ASHRAE 2017), and Addendum AU to ASHRAE Standard 90.1-2016 (ASHRAE 2018a) were adopted in the models for temperature setpoint reset and ventilation calculation. Three models were created to facilitate the OCC practitioners, i.e., the baseline case, the advanced case I, and advanced case II. As illustrated in Figure 6, the baseline represents the case without any sensing technology, and the two advanced models represent occupant presence sensing, and occupant counting sensing respectively.

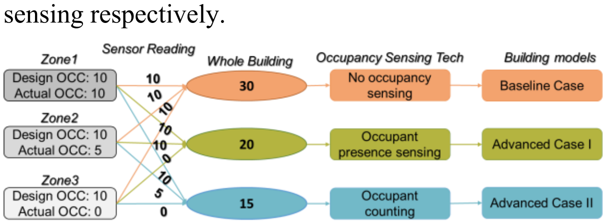


*Figure 6 Occupancy sensing capabilities of the baseline case and two advanced OCC cases*

### *Temperature setback*

The temperature setpoints of the office and conference room were setback for 1 °C and 2 °C respectively during the occupied standby mode following the requirement of Addendum G (ASHRAE 2017).

### *Zone supply airflow rate reset*

The simplified procedure presented in Addendum AU to ASHRAE Standard 90.1-2016 (ASHRAE 2018a) was used to calculate the VAV terminal box minimum damper position.

For the two OCC cases, this minimum damper position was dynamically reset based on the real-time occupancy according to their sensing capabilities.

### *Outdoor air intake for design and operation*

The simplified procedure presented in Addendum AU to ASHRAE Standard 90.1-2016 (ASHRAE 2018a) was used to calculate the design outdoor air intake for each air-handling unit (AHU).

For the baseline case, the outdoor air intake is always no less than this design value in operation due to an absence of the sensing capability.

For the two OCC cases, the outdoor air intake is dynamically reset following the detailed approach and ventilation rate procedure (VRP) presented in ASHRAE Standard 62.1 – 2016 Ventilation for Acceptable Indoor Air Quality (ASHRAE 2016) using the real-time occupancy information. Besides, the minimum outdoor air intake is always capped no more than the design value as required by ASHRAE Guideline 36 (ASHRAE 2018b).

### *Simulation plan*

The simulation plan for the three control scenarios were summarized in Table 4. The EnergyPlus Energy Management System (EMS) module was used to achieve the control sequences.

*Table 4. The control scenarios*

| **Attribute** | **Baseline** | **Advanced I** | **Advanced II** |
|---|---|---|---|
| Occupancy sensing | None | Occupancy Presence Sensing | Occupant Counting |
| Ventilation standard | ASHRAE Standard 62.1- 2019 | Same as previous | Same as previous |
| Operational $V_{ot}$ | Constantly maintains the Design $V_{ou}$, but $E_v$ is reset. | Dynamically reset based on dynamic $V_{ou}$ and $E_v$. Besides, $V_{ot}$ | Same as previous. |

| | | | |
|---|---|---|---|
| | Besides, $V_{ot}$ is capped at no more than Design $V_{ot}$. | is capped at no more than Design $V_{ot}$. | |
| $V_{bz}$ | Fixed based on the ventilation requirement | Dynamic based on presence sensing | Dynamic based on occupant counting |
| Zone minimum supply airflow | Design $V_{oz}$ * 1.5, where $V_{oz}$ varies based on $E_z$ | Design $V_{oz}$ * 1.5, where $V_{oz}$ varies based on $V_{bz}$ and $E_z$ | Same as previous. |
| Temperature setback | None | Yes. 2 °F (1 °C) for offices;4 °F (2 °C) for conference rooms. | Same as previous |
| Zone ventilation shutoff during occupied standby mode. | None | Yes. Zone ventilation is shut off when the zone is unoccupied, and the zone temperature is between the active heating setpoints and active cooling setpoints. | Same as previous |
| VAV logic | Follow the code requirement | Same as previous | Same as previous |

## SIMULATION INFRASTRUCTURE

A comprehensive nationwide impact analysis typically requires a set of simulations covering the representative climate zones and analyzing buildings with different vintages. This study used PNNL's EnergyPlus simulation infrastructure as with a few modifications.

PNNL's EnergyPlus simulation infrastructure was developed to support the progress indicator (PI) and determination analysis for DOE's Building Energy Codes Program. This infrastructure has been used to systematically analyze the energy impact of different energy codes requirement for different building prototypes at different climate(Athalye et al. 2017; Goel et al. 2014; Goel et al. 2017; Thornton et al. 2011). This infrastructure was designed to handle the creation and processing of numerous EnergyPlus simulations at the same time. This infrastructure has four major parts:

- Parameterization of prototype building models
- Automated EnergyPlus IDF creation
- Execution of the simulation process
- Aggregation of simulation result

Specifically, the parameterization of prototype building models is realized through two sets of files: *template* and *parm*. The *template* file is a modified EnergyPlus IDF file with certain EnergyPlus object fields replaced as replaceable variables. The values of the variables are further specified in a parameter file (called *parm* file). Those values are typically depended on specific energy codes requirements or climate zone. In general, a *template* file couples with a *parm* file for the parameterization purpose.

The automation of EnergyPlus creation is realized using a program called *GPARM* developed in Perl at PNNL. This program was used to merge the values specified in the *parm* file with the *template* to create individual simulation cases. One row in the *parm* table represents one simulation case.

The execution of the simulation process is realized through the PNNL Institutional Computing (PIC) system. First, this process executes design day simulation to identify the size of the equipment and generate the baseline model with properly sized equipment. Then, a Python script (newly developed in this project) is used to populate this baseline model to two additional advanced control scenarios (keeping the same equipment size and modify the HVAC control scenarios by either changing the existing EnergyPlus object field specification or adding/modifying EMS codes for advanced occupant centric control strategies)

The last part is to aggregate the simulation result from each case to a summary table. The aggregation is realized using the R script and then populate the result to a pivot table.

In this study, two types of building prototype models were populated via this framework, i.e., large office and medium office. Each building type includes 3*5*16=240 cases, which is composed by the following variations of parameters:

- 16 IECC climate zones in the U.S.
- five versions of ASHRAE 90.1 requirement (i.e., 90.1-2004, 2007, 2010, 2013, 2016)
- three control scenarios (see Table 4)

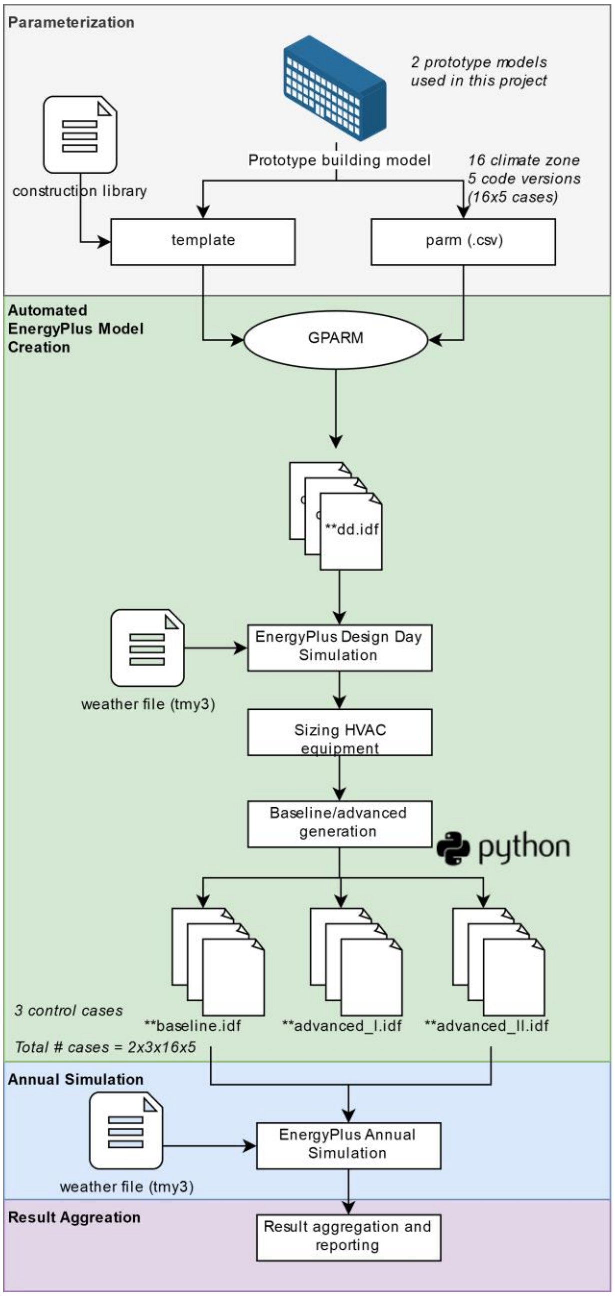


*Figure 7 Flow diagram of the simulation framework based on PNNL's EnergyPlus simulation infrastructure*

The models in this study follow the original DOE commercial prototype model specification for the code compliance requirement, including:

- Interior and exterior lighting power density specification
- Building envelope
- HVAC equipment type, sizing, and efficiency requirement
- Service water heating equipment

with a few amendments to accommodate the needs for this study:

- Changed to detailed zoning and modified the HVAC system configuration accordingly
- Modified the occupancy schedule as discussed in earlier section
- Replaced the original detailed ventilation calculation procedure to the simplified ventilation calculation procedure
- Removed the original demand control ventilation (if any) to better quantify the OCC energy savings.
- Removed occupancy-based egress lighting control specified in addendum ah to 90.1-2013.

## RESULTS

The simulation results are analyzed in this part. It should be noted that the models have not been finalized yet; hence, the energy consumption results may be different if there is any change made to the simulation plan in the future.

### Energy comparison

The HVAC energy consumptions of the medium office model from original CPBM and the baseline medium office model after enhancements were compared in Figure 8. The x-axis represents the HVAC energy consumption of the original medium office model, and the y-axis represents the HVAC energy consumption of the baseline model after the aforementioned enhancements. For most of the cases, the HVAC energy difference was smaller than 30%, while for some extreme case, the difference could be larger. This is because we made huge changes to the existing CPBM, e.g., refining the thermal zoning, adjusting the LPD and EPD based on the detailed zoning plan, totally disabling the VRP module of EnergyPlus, and integrating the simplified procedures into the ventilation calculation.

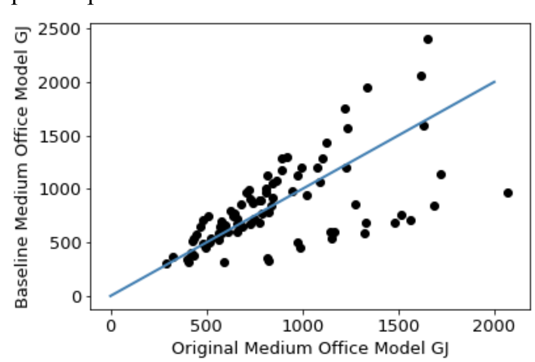


*Figure 8. The HVAC energy comparison before and after the enhancements*

**OCC Energy Savings**

The energy-saving results for the occupancy presence control scenario and the occupant counting control scenario compared with the baseline cases of this study (i.e., the detailed-zoning models) were illustrated in Figure 9 and Figure 10 respectively. The HVAC energy consumption is composed of cooling, heating, and fan energy end-use for medium office, and heating, cooling, pump, fan and dehumidification energy end-use for the large office in this study. The selection of energy end-use if dependent on the HVAC system type.

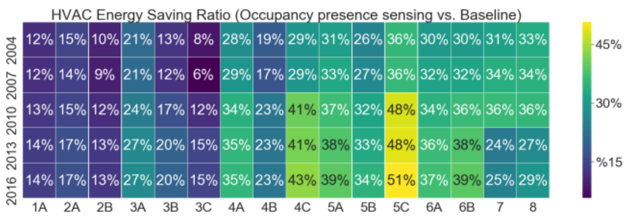


*Figure 9. The energy-saving results for the occupancy presence control scenario compared with the baselines.*

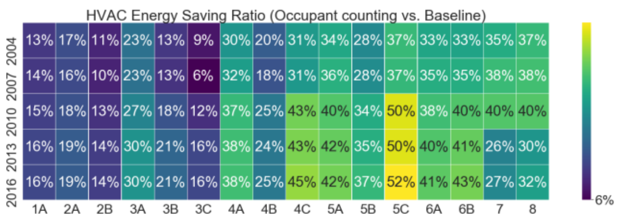


*Figure 10. The energy-saving results for the occupant counting control scenario compared with the baselines.*

- The OCCs could achieve HVAC energy savings in all the 16 climates zones in the U.S. The energy-savings magnitude varies significantly by different climate zones.
- In general, a higher HVAC energy-saving ratio could be achieved in the heating-dominated climate zone comparing to the cooling-dominated climate zone. This is because the reduction in outdoor air intake in the heating mode could result in obvious energy savings compared with the cooling mode.
- The OCC achieves the least HVAC energy saving in climate zone 3C of which the representative city is San Diego, CA. This small HVAV energy saving is probably due to the local mild climate all year round. Since the HVAC load is always small regardless of heating or cooling in climate zone 3C, the energy savings from the reduction in OA intake are not obvious.
- For the proposed office models, the energy-saving from Baseline Case to Advanced Case I is significant, while the additional saving from Advanced Case I to Advanced Case II is minor. This could be due to the fact that under the current occupancy assumption, energy savings of the OCC are mainly from the zone ventilation shut-off during the occupied standby mode, hence the exact difference in occupant numbers does not play a significant role. A further investigation is on the way to fully understand this observation.
- Energy saving from OCC could be affected by the version of ASHRAE Standard 90.1.

## DISCUSSION

**Summary**

In this study, the existing large and medium office models from the U.S. DOE Commercial Prototype Building Models (CPBM) were modified to accommodate the purpose of occupant-centric control (OCC) implementation and evaluation.

Firstly, a detailed rezoning plan was created to add the zoning diversity (e.g., closed office, open office, conference room) to the original medium and large office models in the CPBM. Then, two OCC cases were generated utilizing the occupancy presnece sensing and occupant counting technologies. Next, a unique set of dynamic occupancy schedules were generated using a statistical tool for each room to represent the occupancy variation. Finally, the refined models were extended to different versions of ASHRAE standards (e.g., ASHRAE Standard 90.1-2004, 2007 and 2010) and various U.S. climate zones following the code requirement.

**Future work**

In the future, the following work will be completed to enhance the feasibility of this simulation suite:

- The current simulation plan will be further reviewed to better represent the common practice in the real condition.
- More building energy models will be incorporated to this simulation suite, e.g., the primary school, large hotel, and residential home, to satisfy the versatile needs from the OCC practitioners.

## ACKNOWLEDGMENTS


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