DEVELOPMENT OF A FLEXIBLE, MULTIZONE, MULTIFAMILY BUILDING SIMULATION MODEL

Mini Malhotra and Piljae Im
Oak Ridge National Laboratory, Oak Ridge, TN

malhotram@ornl.gov, imp1@ornl.gov

ABSTRACT

As weatherization of multifamily buildings becomes more widespread, improvement is needed in energy audit tools for multifamily buildings. On the wish list of field experts is the capability to model multizone buildings (i.e., one thermal zone per dwelling unit) with simplified user input to improve analysis of decentralized and centralized HVAC and domestic hot water systems without creating detailed building models. To provide the desired capabilities, development of an enhanced energy audit tool was begun in 2011. The tool is a strategically structured, flexible, one-zone-per-unit DOE-2.1e model coupled with a simplified user interface to model small to large multifamily buildings with decentralized or centralized systems and associated energy measures. This paper describes the modeling concept and its implementation.

INTRODUCTION

Increasing attention to multifamily building energy use and weatherization led to an assessment of needs related to multifamily energy audits. Through two Web-based meetings held in November 2010, input was obtained from two field personnel groups from across the United States—multifamily audit method experts and audit tool users—regarding existing audit tools and methods, issues, potential improvements, and desired capabilities. Malhotra et al. (2012) describes the background leading to this effort; recommendations, issues and trends; the influence of national input on development of a new multifamily energy audit tool for the Weatherization Assistance Program (WAP) (US DOE 2012); and the conceptual plan for design, development, and integration of its key analysis components.

Following recommendations from practitioners and experts, development of a new energy audit tool for multifamily weatherization began as a collaborative effort by Oak Ridge National Laboratory (ORNL) and Lawrence Berkeley National Laboratory (LBNL). The energy calculation engine (including the simulation model and supplementary calculation modules) is shared by ORNL's Weatherization Assistant (weatherization.ornl.gov/assistant.shtml) and LBNL's Home Energy Saver^{TM} *pro* (HES*pro*) (hespro.lbl.gov/).

On the ORNL side, the energy calculation engine is coupled with a user interface and output reporting capabilities based on WAP regulations and guidelines to develop the Multifamily Tool for Energy Audits (MulTEA). MulTEA is part of the Web-based Weatherization Assistant suite of tools that also includes energy audit tools for single-family and manufactured homes. On the LBNL side, same engine will be used in HESpro to expand it to handle multifamily buildings.

The new multifamily simulation model is designed to address small and large multifamily buildings with decentralized and centralized heating, ventilation, and air-conditioning (HVAC) and domestic hot water (DHW) systems. Version 1 of MulTEA, which addresses small multifamily buildings with decentralized HVAC systems, is currently in field testing. The capability to model large buildings and centralized systems will be incorporated in Version 2. This paper describes the concept of a multizone, flexible DOE 2.1e simulation model formulated to address the need for detailed modeling capability with a simplified user interface.

DESIRED MODELING AND ANALYSIS CAPABILITIES

Input from user group participants in the Web-based meetings indicated that existing DOE-approved audit tools pose limitations in whole-building energy analysis with multiple systems. The existing tools allow modeling of either separate dwelling units with individual systems, or a single-zone building served by one primary heating system. They do not account for interactions between zones and systems. The former approach works acceptably for small multifamily buildings but

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has limited analysis capability for whole-building retrofit measures. The latter approach has worked reasonably well for large buildings with one central system, but it requires aggregating system parameters and tricking the tool into providing a one-system answer for decentralized systems. The available tools perform better for buildings in heating-dominated climates, rather than in cooling-dominated climates.

Input from audit method experts indicated the need for important improvements, including better handling of multiple zones and decentralized systems, improved treatment of ventilation systems and infiltration assessments, inclusion of rules-based savings calculations, more flexibility with heating or cooling equipment efficiencies, and utility bill reconciliation.

FUNCTIONALITY AND USABILITY REQUIREMENTS

Following the national input for desired improvements in modeling and analysis capabilities, an assessment of functionality and usability requirements of the audit tool was performed. Target building characteristics (size and configuration of the building and systems) and the skill levels of target users were important considerations in determining the modeling approach and design of the user interface.

Target Building Characteristics

For WAP energy audit purposes, DOE considers multifamily buildings to be those containing five dwelling units or more (MF 5+). A review of the 2005 Residential Energy Consumption Survey (RECS) (US EIA 2009) data revealed statistics for building scale and system types by region for MF 5+ buildings.

There are approximately 17 million dwelling units in MF 5+ buildings in the United States. Figure 1 shows the distribution of dwelling units by major census regions and the variation across regions. Although RECS data do not address multifamily "buildings" directly, analysis of the data using derived parameters indicates that the distribution of buildings by region is approximately the same as the distribution of the dwelling units. Also, 70–80% of all MF 5+ dwelling units are in "small" multifamily buildings in all four regions.

Figure 1: Distribution of MF 5+ dwelling units across the United States by major census region

Statistics for heating system type show that about 75% of all dwelling units in MF 5+ buildings have simpler systems. Figure 2 shows a distribution of dwelling unit populations with simpler (decentralized) and complex (centralized) systems by major census region. It indicates that complex systems are dominant in the Northeast and decreasingly prevalent moving to the Midwest, South, and West.

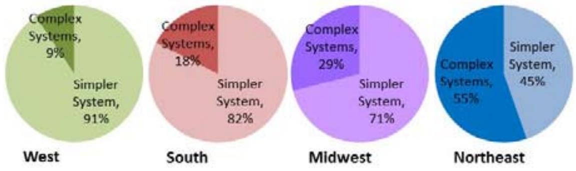

Figure 2: Distribution of MF 5+ dwelling units by system types in major US census regions

The national input also indicates that multifamily housing types ranging from small buildings to high-rise apartments are found in almost all states. Small multifamily buildings being audited range from walk-up buildings of up to three stories with central steam heating systems, to garden-style apartments with individual HVAC systems (and sometimes a central system for common areas).

The building scale and system configuration are two key sources of variation in multifamily buildings that may require different methods of handling. Multifamily building typologies add to this requirement by multiple degrees. A review of multifamily housing types shows that multifamily building typologies vary widely (CDI 2011, HUD 2012) and cannot all be analyzed using one model. For example, compact, box-shape buildings with double-loaded corridors and protected entrances; apartments with breezeways or open verandas; and garden-style apartments similar to single-family units—all require different models. To address these building and system configurations, either a flexible building model or multiple modeling templates are needed.

Target Users and Skill Level

To collect modeling inputs efficiently, it is important to consider the users' level of skill at obtaining building data in determining the level of detail to include in the user interface. It is important to note that the multifamily audit tool would primarily be used by energy auditors in weatherization agencies to conduct energy audits in multifamily buildings.

In general, the skill level of a multifamily building energy auditor can be assumed to be advanced, as these auditors must meet the national workforce guidelines for multifamily building energy upgrades (BPI 2008) and obtain required certification(s) on the national training platform[1]. However, there may be instances when agencies/auditors mostly dealing with single-family weatherization begin to audit small multifamily buildings. Therefore, some level of conformity is required between the existing single-family audit tools and planned multifamily audit tool.

MODELING APPROACH

Energy simulation is a very powerful approach, and its benefits are often enticing. However, an excessive focus on detailed modeling may provide only marginal benefits and compromise the usability of the tool. At the same time, oversimplification of audit inputs may undermine the benefits of simulation. Therefore, optimal levels of modeling detail and audit input simplification are needed. The following discussion presents general criteria that guided the modeling approach.

Zoning

Multifamily buildings typically have dwelling units facing different orientations, and may have dissimilar floors, common areas (open or enclosed, conditioned or unconditioned), and vertically connected spaces (e.g., stairwell and shafts). Multiple thermal zones are required to adequately model the impact of the energy interactions of a zone with the outdoors and with attached dissimilar zones, and to evaluate zone-specific retrofit measures. Modeling the energy interactions of a zone with the outdoors requires separate zones for corner units and embedded units facing different orientations. Modeling a zone's energy interactions with attached dissimilar zones requires separate zones for common areas.

Dividing the building into too many zones may increase modeling errors. Therefore, for Version 1 of the tool to have a reasonable number of zones, only four typical floors (i.e., top floor, intermediate floor with a floor-multiplier, first floor, and below-ground floor) are modeled. On each floor, multiple thermal zones for dwelling units having dissimilar exposures, and one thermal zone each for enclosed hallways (conditioned or unconditioned), other conditioned spaces aggregated, and other unconditioned spaces aggregated are modeled. Zones for an attic space and a crawlspace are also incorporated in the model. Figure 3 shows examples of multifamily building configurations addressed by the proposed zoning scheme, and highlights typical floors and dwelling unit zones required for modeling different building configurations.

[1] The workforce guidelines and training platform modules of the technical standards are currently in development. Until they are finalized, the interim standards document can be consulted to understand the skill levels required.

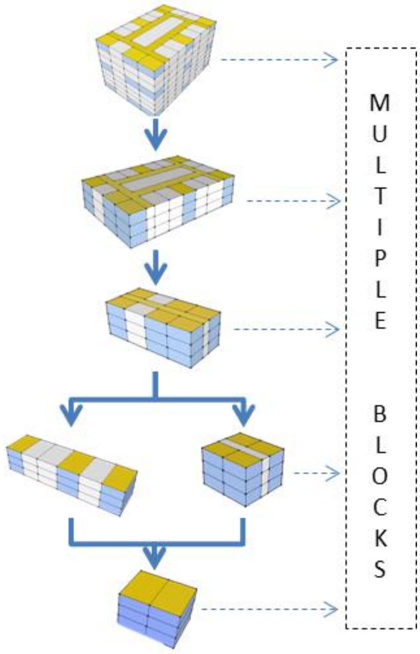

Figure 3: Examples of multifamily building configurations addressed by the proposed zoning scheme

System Assignment

HVAC and DHW systems in multifamily buildings may be centralized, decentralized, or a combination of both. The characteristics, loads seen by the system, operation and efficiency under part-load conditions, and retrofit measures are all quite different for centralized versus decentralized systems. Therefore, modeling systems and assigning them to zones to reasonably represent the installed configuration is important. The model is developed to handle decentralized systems in all the thermal zones described, a centralized system serving a whole building, or a combination of decentralized systems serving dwelling units and a centralized system serving common areas of the building.

Component Modeling

Building components and associated measures that impact heating or cooling energy use directly or indirectly (e.g., shell, HVAC system, indoor lighting and appliances) must be analyzed as part of the whole-building energy simulation. However, some of these components and measures (e.g., infiltration, HVAC system tune-up) are hard to model and require separate analysis methods, such as side calculations and evidence-based energy performance or savings estimates. For other components and measures that have noninteractive energy impacts (e.g., exterior lighting and equipment, DHW system) or that are better handled outside DOE-2 (e.g., distribution system), separate analysis methods are preferred.

The level of analysis and modeling detail is determined by considering the role and treatment of a component in the building energy audit process. In general, the WAP allows retrofit measures that involve materials listed in Appendix A of 10 CFR Part 440 (US GPO 2005) or that are approved by DOE on a case-by-case basis. Analysis of these measures requires detailed modeling of components that are candidates for retrofit. Other components may be analyzed using aggregated or averaged inputs without compromising the modeling benefits.

Through aggregated or averaged modeling inputs, variations among dwelling units in terms of characteristics of the shell component, indoor conditions, systems, occupancy, and schedules are handled. Thus all dwelling units are modeled as identical zones in all respects except variations in exposure, which are handled well through the zoning scheme described previously. Aggregated or averaged modeling inputs are also found useful for combining multiple common areas existing on a floor as one thermal zone.

Implementation of Modeling Approach

The modeling approach described is implemented at two levels, the front-end graphical user interface (GUI) and the backend DOE-2.1e simulation model (BDL, or building description language), connected through backend calculations that convert GUI inputs to BDL inputs. These key components collectively ensure that the desired modeling capabilities are addressed in the BDL without complicating the data input process on the GUI. Backend calculations also prepare inputs for the supplementary analysis modules outside DOE-2 simulation. These are described in the following sections.

USER INTERFACE

The GUI data input forms are designed for describing the building, shell, systems, lighting, and appliances to model all targeted zones of the building to the desired level of detail. Efficiently incorporating all relevant building inputs for a wide range of possible building scenarios required a judicious layout of data input fields on the GUI forms.

Figures 4 through 6 show Building, Walls and HVAC systems forms, respectively, to demonstrate how the building, shell and system component details are laid out in the interface.

Building Form

The Building form (Figure 4) collects information about the size and configuration of the building and its spaces. Specific inferences from user inputs that allow the simplification of input requirements are made as follows:

- The existence of the top, intermediate, first, and below-ground floors, and the floor multiplier for the intermediate floor are determined from the user inputs for number of floors above and below grade.
- The existence of zones (i.e., dwelling units, enclosed hallways, other conditioned spaces, and other unconditioned spaces) on different floors is determined from the user inputs for area of zones by level. The existence of an attic and a crawlspace is determined implicitly from the user inputs for roof type (i.e., attic roof) and floor type (i.e., above-crawlspace floor) on the shell forms.
- The existence of typical dwelling units having different exposures, and the multipliers for dwelling units with identical exposures are determined from the user inputs for number of units by exposed sides and floor level in the graphical input fields.
- The building shape is approximated from the user selection for building configuration that lists typical compact and winged layouts. The arrangement of dwelling units in the building is approximated from the user selection for building configuration combined with hallway configuration (i.e., single-loaded, double-loaded, nonexistent). These approximations help estimate the coordinates of zones, which are required for modeling the impact of building self-shading. Shading from nearby objects (e.g., vegetation, neighboring buildings) would require additional inputs for their height and distance from the building.

Shell Forms

The shell forms describe the construction, size, and retrofit measures for walls (Figure 5), roof, floors (i.e., surface components), windows, and doors (i.e., subsurface components). Key considerations behind the shell forms are as follows:

- Multiple exterior walls, underground walls, and partition walls can be described using the Wall form; multiple segments of attic roofs, cathedral roofs, and flat roofs can be defined using the Roof form; and multiple ground-coupled floors, exposed floors, above-crawlspace floors, and interior floors can be described using the Floor form.
- All heat transfer components must be described explicitly, including partitions that are considered for retrofit. Description of adiabatic surfaces is not required.[2]

[2] To account for the thermal mass of interior surfaces in a zone, the model determines adiabatic wall area by subtracting user-defined zone-specific wall area from estimated total enclosing wall area (i.e., based on an assumed zone perimeter-to-floor area ratio). Adiabatic floor area is determined from user-defined zone area minus area of user-defined floor component assigned to that zone.

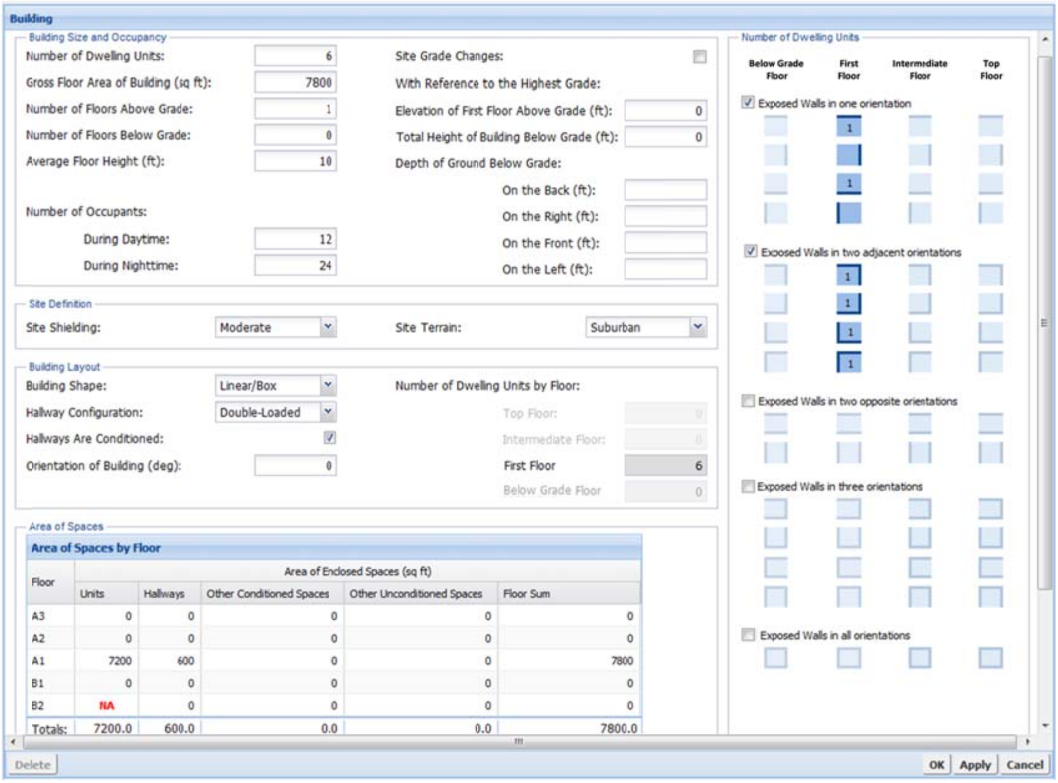

Figure 4: Building form for describing overall building configuration, area of spaces, and number of dwelling units

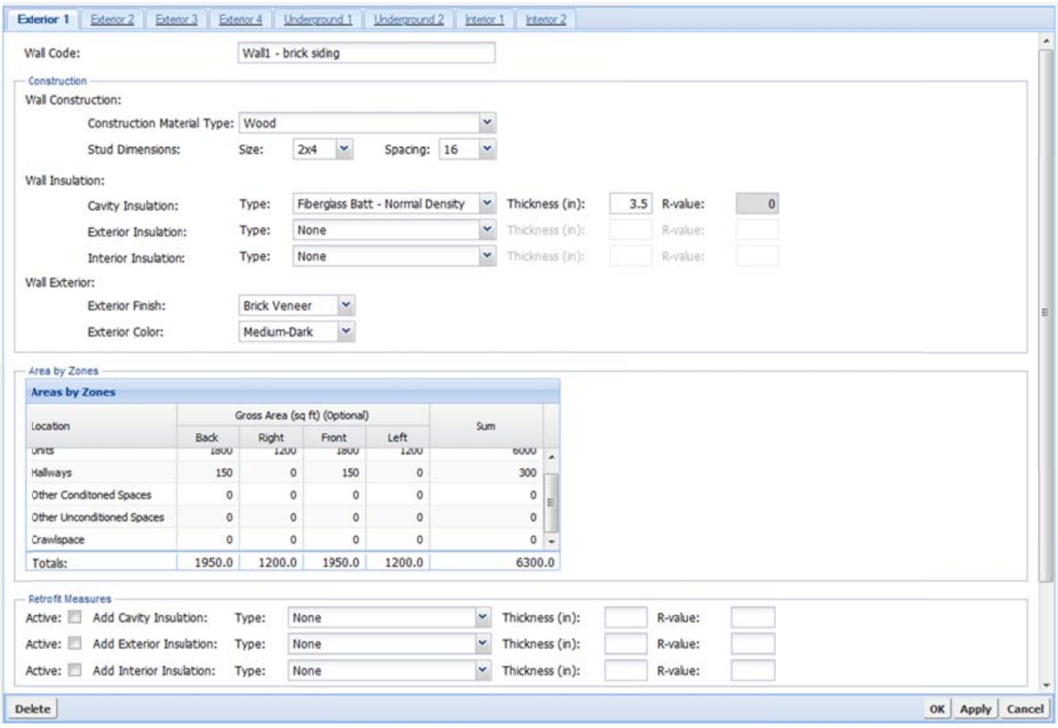

Figure 5: Wall form for describing construction, area, and retrofit measures

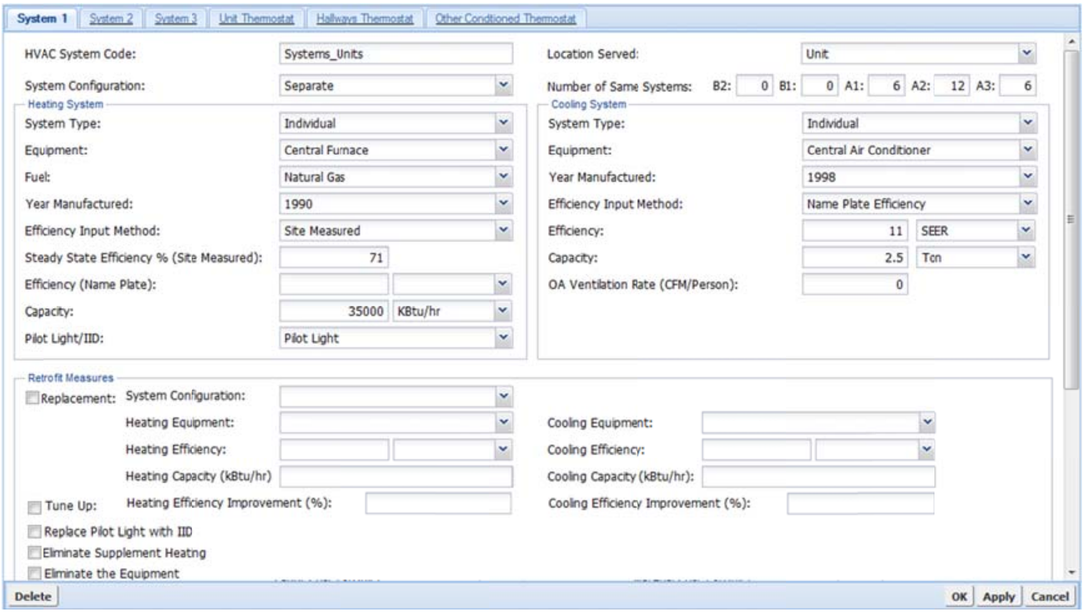

Figure 6: HVAC form for describing system type, size, efficiency, and retrofit measures

- Multiple segments or instances of the same construction, which are considered for different retrofit measures, must be described separately.
- To accurately assign surfaces and sub-surfaces to individual zones, zone- and orientation-specific user inputs are required for wall area (and exposed perimeter for ground-coupled walls), zone- and floor level-specific user inputs for roof and floor area (and exposed perimeter for ground-coupled floors), and zone- and parent wall-specific user inputs for the number of windows and doors.

Systems Forms

The systems forms describe the characteristics (i.e., type, size, and efficiency), operation, and retrofit measures for HVAC systems (Figure 6) and DHW systems. Key considerations behind the systems forms are as follows:

- Decentralized HVAC systems can be described. All systems must have zone and level assignments. All conditioned zones of the building must have at least one system assigned. Heating-only and cooling-only systems can be described.
- Multiple HVAC systems must be described to address (1) variation in system characteristics, (2) difference in zone assignment, (3) multiple equipment serving one zone, or (4) identical systems considered for different retrofit measures.[3]
- Centralized or decentralized DHW systems, as well as hot water distribution system details, can be described. This allows analysis of a range of equipment, operation, and distribution system component-specific retrofit measures.[4]

Lighting and Appliance Forms

The lighting and appliance forms require only zone-specific inputs for the base-case lighting and equipment power densities and scale of usage. In addition, exterior lighting and equipment (e.g., elevators) can be described as installed wattage and hours of operation. The lighting retrofit measures can be described as existing lighting component-specific measures (e.g., lamp replacement). Similarly, the equipment retrofit measures can be described as existing equipment-specific measures (e.g., replacement of existing refrigerators or laundry equipment). GUI backend calculations convert noninteractive annual lighting/equipment energy savings into reduced power densities for DOE-2 simulation in order to account for the impact of internal heat gain on heating and cooling energy use.

DOE-2 SIMULATION MODEL

BDL Structure

The BDL is structured strategically to create a flexible, multizone model of a multifamily building, which could handle a wide range of possible building scenarios. This was accomplished through DOE-2 macro commands: include macros (##include), definition macros (##def),

[3] The BDL uses aggregated/averaged system inputs to model one system per zone and identical systems in all dwelling units of the building. Common areas on different floors are modeled with different HVAC systems.

[4] DHW system and associated retrofit measures are analyzed using a new separate analysis model developed by LBNL.

and conditional macros (##if) (Winkelmann et al. 1993). The BDL is developed in segments (i.e., include-files) that are pulled together in the BDL input stream by a parent input file. This file calls all level 1 include-files, some of which call level 2 include-files (e.g., inclusion of level 2 zone-specific surface description in level 1 space description). Blocks of inputs for similar commands and commands that appear multiple times are defined collectively using definition macros. The definition macros optionally use arguments (i.e., variables that can be assigned a value at the time the definitions are referenced in the BDL). Conditional macros are extensively used for including or excluding portions of codes based on the existence and type of building and system components inferred from the GUI inputs. Structuring the BDL in this manner offers many advantages in terms of its development and testing:

- Development of the BDL as a set of include-files, once it is created, allows parallel development of its individual parts, which can be tested with the remaining parts seamlessly;
- Use of definition macros with arguments for repetitive blocks of inputs makes the BDL more concise, minimizing modeling errors. Errors, if introduced, are easy to identify and fix;
- Defining macros collectively for similar commands allows faster development of the BDL and prevents omission, duplication, or other modeling errors;
- New modeling entities (e.g., zones and surfaces) can be defined and added easily;
- Conditional macros allow the BDL to be flexible yet precise enough to address any number of floors, any arrangement of dwelling units, and the existence of common spaces in the building.

Key Modules of the BDL

The following files collectively build a complete building model of a multifamily building:

main.inp

This is the main BDL input file that pulls all level 1 include-files together, including those required under LOADS and SYSTEMS subprograms.[5] All other files described below (**.inc*) are include-files.

userInput.inc

This level 1 include-file defines all macros required to receive GUI inputs and preprocessed values derived from GUI inputs, and passes them downstream. Examples of GUI inputs include general building inputs such as area of spaces, number of floors, and number of dwelling units. Examples of preprocessed modeling inputs include material properties derived from descriptive user inputs for construction.

preCalc.inc

The *useInput.inc* include-file contains a limited number of macros that are collected as GUI input or preprocessed values. *preCalc.inc*, a level 1 include-file, defines additional macros required by the BDL based on those already defined in *userInput.inc*.

def<entity>.inc

These level 1 include-files contain macro definitions of construction layers, surface components, spaces, zones, and systems, which are referenced multiple times in the BDL. For example, all dwelling units that face a specific orientation have identical walls, windows, and doors; and all dwelling units on a specific floor have identical floors, roofs, and ceilings. These identical shell components are modeled in multiple zones simply by referring to macro definitions rather than using expanded commands. Furthermore, all walls, roofs, ceilings, and floors are assumed to have up to a five-layer construction assembly. Using a five-argument macro definition, all constructions are modeled simply by referring to the same macro definition and assigning materials to the five arguments.

<entity>.inc

These level 1 include-files are used for describing schedules, materials, layers, construction, glass types, and space conditions. These include-files use expanded commands or refer to macro definitions defined previously in various *def<entity>.inc* include-files.

SPACE.inc

This level 1 include-file is the core of the LOADS subprogram that is coded to be flexible by using conditional macros for including or excluding floor levels, zones, surfaces, and sub-surfaces. Figure 3 indicates how this include-file can generate multiple building configurations by using the flexible modeling scheme. These include-files use macro definitions of spaces defined in *defSPACE.inc*. The key points of this scheme, in parallel with the key points of the GUI, are as follows:

- Only typical floors are modeled, which include a top floor, an intermediate floor with floor multipliers, a first floor, and a below-grade floor.
- Six enclosed zone-types are modeled: dwelling unit, enclosed hallway, other conditioned space, other unconditioned space, attic, and crawlspace.[6] All zone types except attic and crawlspace can exist on

[5] PLANT inputs will be expanded in Version 2 of MulTEA.

[6] Other conditioned spaces and other unconditioned spaces combine all common spaces that are part of the building. More spaces can be added (e.g., modeled as separate zone types, as needed, as long as such a change is made at all levels: defining areas, surfaces, internal loads, and systems).

all floor levels. Among these, dwelling units having dissimilar exposures are modeled as separate zones, and dwelling units with identical exposures are modeled using multipliers.

- Under each zone, a set of orientation-specific include-files are called for modeling walls, windows and doors, and floor level-specific include-files are called for modeling floor and ceiling/roof.
- The zones are assumed to be rectangular in plan. This allows the coordinates of shell components to be derived easily using the dimensions of the enclosing surface components.

<Vsurf><zone><orientation>.inc and
<Hsurf><zone>< level>.inc

These level 2 include-files define multiple walls, windows, and doors (i.e., vertical surfaces and subsurfaces), and multiple floors, ceilings and roofs (i.e., horizontal surfaces) under conditional macros, which include or exclude multiple instances of these surfaces based on the user inputs. These include-files use macro definitions of surfaces and sub-surfaces defined in various *def<entity>.inc* include-files.

ZONE.inc and *SYSTEM.inc*

These level 1 include-files are the core of the SYSTEMS subprogram, and use the same conditional macros as described in SPACE.inc for including or excluding zones and assigning systems to these zones. These include-files use macro definitions of zones and systems defined in *defZONE.inc* and *defSYSTEM.inc.*

SUMMARY

This paper presents the flexible, multizone modeling concept formulated for the development of a multifamily building energy audit tool for the WAP. This effort is in response to the need for an improved audit tool with the basic ability to model multiple zones and multiple systems (i.e., multiple equipment of a central system or multiple decentralized systems). The design of the user interface and the structure of the BDL are described to demonstrate the implementation of the modeling concept. The modeling approach allows rapid development and testing of the BDL. This same approach could be used directly for building types such as hotels, motels, and dormitories, and followed for creating custom templates for other building types for which a single zoning scheme is not applicable.

The current version of this tool addresses low- to mid-rise multifamily buildings with decentralized HVAC systems. For high-rise multifamily buildings, additional capabilities need to be added, such as modeling of spaces spanning multiple floors as separate zones (e.g., stairwells, elevators, ventilation shafts, garbage chutes), improved analysis of infiltration, and modeling of centralized HVAC systems, including ventilation-only systems. For multiple building developments (e.g., those served by a district heating/cooling system), a revised user interface would be required to allow description of multiple buildings in blocks, and additional modules would be needed in the BDL to model plant equipment.

For developing any similar modeling system, the development steps of analyzing desired/required capabilities, building stock configurations, zoning possibilities, tradeoffs of input simplicity versus modeling complexity, and feasibility of implementation approach using a selected modeling engine, would still be needed.

ACKNOWLEDGMENT

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