STREAMLINED MULTIZONE MODEL CREATION

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ABSTRACT

Multizone modeling for the simulation of airflow and contaminant transport in buildings is intermediate in resolution and complexity between the extremes represented by single-zone models and computational fluid dynamics. The model input time requirements for a multizone building model are likely less than that required for the construction of computational fluid dynamics model of a building subset, but are likely more than required for a single-zone building model. This paper describes techniques intended to reduce the time required to construct a multizone representation of a building and presents data demonstrating their effectiveness. The airflow network that models the movement of air is constructed semi-automatically from input geometrical information, simple mechanical systems descriptions, and high-level weather parameters. The time required for model construction with this streamlined input procedure is measured using an implementation of the streamlined procedures. Model creation time is found to be approximately one quarter of the time required to construct the same model using standard techniques. When calibrated, the resulting models are sufficiently representative of the buildings under study to be useful for analytical and design studies.

INTRODUCTION

The many techniques available for airflow simulation in the indoor environment may be distinguished in terms of the length scale that is resolved. At the largest scales, a building is represented in terms of a set of scalar properties. With this approach, also called a single-zone approach, it is assumed that variations in these properties throughout the building are negligible. At the smallest scales, the governing equations of fluid flow are solved by computational fluid dynamics (CFD) methods. CFD methods are available over a range of scales, and a properly executed solution will describe a solution domain in terms of vector-valued properties.

Multizone airflow modeling, also called nodal airflow modeling, is an intermediate technique between the detailed, microscopic approach of computational fluid dynamics and the high-level, macroscopic approach of single-zone methods. In this approach, the building is divided into a set of regions of interest, called zones or nodes. Airflow between nodes is constrained to a set of connecting paths. These airflow paths may represent doorways, windows, leakage due to construction flaws, ducts, and other routes by which air may travel from zone to zone. This operation decomposes a building into an airflow network, as shown in Figure 1.
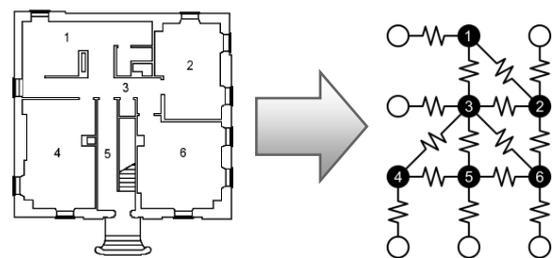

Figure 1 Schematic of a typical MZ model

Some interzonal flows may be specified (e.g. the flow rate of a fan), but most flows will be determined by the pressure differences between two connected zones and the resistance to flow of the leakage paths. The most common representation of the airflow in a multizone model is the nonlinear power law

$$Q = C\Delta P^n, \tag{1}$$

Where Q is the flow rate, C is a constant, ΔP is the difference in pressure between the two zones connected by the path, and n is the flow exponent (typically less than 1, often 0.65). Each airflow path represented in this way may be thought of as a distinct resistance to flow. The resulting network is well suited to the element-based solution approach advocated by Axley and Grot (1989), in which the building model is made up of a set of nodes connected by airflow elements. The equations that are to be solved may be assembled in a process very similar to the finite element assembly process. The resulting resistance network is then solved

to determine the airflow between zones, typically using a Newton-type iterative procedure. This approach results in a (nonlinear) system of equations with the number of degrees of freedom on the order of the number of zones, which is far less than that required for CFD solutions (many millions) and more than that for single-zone solutions (typically no more than order 10).

It should be noted that, for any non-trivial building, modeling choices will be required before a complete model can be constructed. In Figure 1, a network of seven zones represents the first level of a small building. The entry hallway and stairwell (labeled as number 5 in both drawings) and the connecting hallway (labeled as 3 in both drawings) have been represented as single nodes. Depending upon the nature of the partitions separating zone 1 and zone 3, these spaces might be represented as a single zone. Similarly, zone 5 might be better represented as two zones: one for the hallway and one for the stairs. This sort of modeling choice arises frequently in multizone model development.

It is difficult to describe a "typical" multizone model development process since there are many ways to arrive at the network shown in Figure 1. The processes used vary for many reasons, including the availability (or lack of availability) of information on the building to be studied. Sources for building information include drawings, equipment manuals, operators, and inspection. The collection of building information may be very time consuming, and little can be done to shorten this process if the information is not easily obtainable. The collected data usually needs to be reformatted for the modeling software, which may also be very time consuming and typically requires a degree of familiarity with the software. All of these factors contribute to the investment in time and money required to develop a proper model.

This paper describes an effort to reduce the burden upon the modeler by both reducing the quantity of information required to develop a model and the difficulty in translating that information into suitable form for use by multizone modeling software. This reduction in complexity will reduce the time required for the creation of models and lower barriers to the use of multizone modeling in practice. The reduction in time is demonstrated with a software implementation of the streamlined methodology.

SOFTWARE CONSIDERATIONS

A number of air flow modeling packages utilize the multizone methodology. CONTAM (Walton and Dols 2010) is developed and maintained by the National Institute of Standards and Technology (NIST). COMIS (Feustel and Rayner-Hooson 1990) was developed by an international group of experts and is still in active

use. Recently, a Modelica package for multizone modeling was developed (Wetter 2006). The discussion here focuses on CONTAM because it is under active development, freely available, and widely used, but it is expected that the techniques described likely apply to other packages.
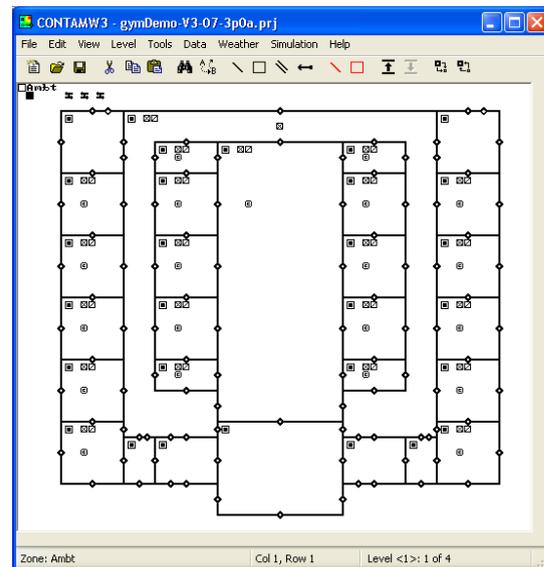

Figure 2 The ContamW user interface

CONTAM is comprised of a number of separate programs, most importantly, the ContamW interface and the ContamX solver. The ContamW interface may be described as a hybrid of a building floor plan and a building schematic, with a certain degree of planning required to obtain a model that both describes the building under study and facilitates post-processing of results. The process is menu- and dialog-driven using ContamW's sketchpad, which allows for the construction of models in a schematic form with some integration of spatial positioning. The sketchpad is a rectangular grid of square cells that represent model elements and how they interact. Each cell in the sketchpad grid can usually hold one icon that describes some aspect of the model, for example, a leakage path, as shown in Figure 2 – each item shown in the display window is an icon of one type or another. Key elements of the sketchpad interface are:

- The building is divided into a discrete set of vertical levels.

- Each level is described in terms of a 2 dimensional array of cells that may contain icons describing elements of a level, including: walls and partitions, air flow paths, contaminant sources and sinks, and HVAC equipment.

- Icons for many elements of a building model are placed individually. While there are placement rules, the user is mostly left to decide where icons should be placed.

For experienced users, the sketchpad interface is an extremely powerful tool, but for new users it can be intimidating. The user draws each zone as a set of enclosed cells, and then adds paths between neighboring zones and any other required attributes. Typically, each attribute is added by adding or modifying an icon.

MODEL CREATION

As noted above, there are many ways to create an airflow network that models a building. Some of this variability may be attributed simply to modeler preferences, as ContamW allows the construction process to proceed in almost any order. In ContamW, this is done explicitly with icons representing the components. As shown in Figure 2, each zone is an enclosed space on the sketchpad, and each airflow path is shown as an icon (with different icons for leakage paths, supply points, return points, and other model elements). Once simulation results are available, the results may be displayed on the sketchpad. The typical modeling process involves 4 steps (not necessarily in this order):

1. Information on the building is gathered from drawings and other sources (possibly including operational information from the responsible parties). This step may require a significant investment of time and energy.

2. Walls or partitions that are deemed sufficiently important are drawn (this places wall icons) and zones are specified by placing zone icons within regions delineated by walls.

3. Airflow paths are defined by placing path icons on surfaces separating zones.

4. HVAC elements are input with icons representing the connections between air handling systems.

Additional steps may be taken depending upon the type of analysis that is to be done. For example, additional icons representing CO_2 sources would be placed for certain types of ventilation studies. The usual expectation with CONTAM (and many other simulation tools) is that the model will be constructed using a graphical user interface (GUI). That is, the user will sit in front of a computer and manually enter the necessary information to create a model. Any attempt to streamline the model development process must honor this mode of model creation, but it also must consider other modes and the possible impact that changes to the process may have.

There are two additional modes of model creation to consider. First, it is often desirable to take a previously created model and generate a set of new models with one or more parameters varied. This "parametric mode" of model creation is useful in studies in which a large number of design parameters may need to be investigated. Second, there are situations in which it may be desirable to automatically generate a multizone model. When multiple analysis packages are to be used to study a building, it is natural to wish to drive model creation from a single data source. Each of these modes has distinct challenges and benefits, and there are many ways to include all three in an overall methodology. Care must be taken that support of one mode does not adversely affect other paths to the creation of multizone models.

Graphical Model Creation

CONTAM models are usually created with the ContamW graphical user interface. The schematic nature of the sketchpad interface can be confusing for first-time users, and it is easy for beginners to make mistakes that may not be easy to see. A typical issue is to forget to place all of the flow paths that were intended, resulting in a model that may not behave as expected. This same schematic input method also presents opportunities for streamlining. Since the model doesn't require the detailed shapes of walls or spaces within the building, it is not necessary to gather that sort of information. Therefore, while it might be viewed as desirable to have three-dimensional model visualizations, it is highly unlikely that a three-dimensional input tool would by itself represent a simplification of the process. Rather, any directly user-driven creation process should focus on keeping the number of inputs down rather than adding different inputs (e.g. three-dimensional partition details). Significant reductions of model input time are possible by improving the efficiency of sketchpad input rather than looking for a complete replacement.

Parametric Model Creation

The parametric mode of model creation requires a fully realized model in an appropriate form for modification. One or more parameters of interest are selected and these parameters are varied, producing a set of models that cover a range of parameter values. This process has been used with CONTAM by DeGraw and Bahnfleth (2011) to compute security assessments of buildings in response to extreme indoor air quality events. In that case, new models are generated from the baseline model automatically. The typical parametric modeling process involves the creation of many more models than would likely be practical or feasible to examine manually, but it is not unusual to do spot checks or post processing of individual cases to gain insight into what

is happening as parameters are varied. A streamlined modeling process that supports parametric model creation should make many parameters as easy as possible to access, but should not preclude access to the models themselves. CONTAM is ideal for this purpose, as the input files are plain text and relatively easy to parse automatically to modify parameters. Thus, a simplified approach should make parametric modeling easier since model simplifications should result in easier variation of parameters.

Automatic Model Creation

Automatic creation of models is an area of increased interest, especially in the area of building information modeling (BIM). Typically, the source data for such a process is some other representation of a building, so the primary issue is one of translation. Basarkar and Swami (2006) describe a program to translate an Industry Foundation Classes (IFC) representation of a building into a CONTAM model. Dols et al. (2009) use a converter to obtain an initial version of a model from an IFC-formatted file. Difficulties arise if a detailed model is desired due to incompatibilities between the IFC representation of building elements and the requirements of a detailed multizone airflow model. A less detailed approach would be beneficial to any effort to produce a model automatically, as it is less likely to depend upon the spatial arrangement of components or the details of a particular data source. This is an area of ongoing research, particularly with respect to the formal process by which BIM-type data is made available for translation or conversion into modeling software inputs.

STREAMLINING INPUT

To reduce the time required to create multizone models, it is important to understand the data that is required to construct a model. The typical process for the creation of multizone models tends to treat most building-related inputs as being specific to the current building. Building-specific information describes some aspect particular to the present building under study. These data are low-level and detail-oriented in nature. Examples include level heights and placement of intakes and exhausts. Many other characteristics may be expressed either in generic terms or as high-level descriptions that are not specific to the building under study. Examples include the building type (e.g. commercial), the building use (e.g. education), the thermal zoning strategy (e.g. perimeter-core), and site-related information (e.g. surrounded by other buildings). Not all of these characteristics are directly useful for multizone modeling. A particularly important example of site-related information that is useful for multizone modeling is weather data. The wind pressures that act on a building play a very important role in air movement inside the building, but weather data is best associated with geographic location and the broad building type, not with details of the particular building. Of these two types of building information, the non-building-specific data is generally easier to obtain, and sometimes can be determined by simply looking at a building (e.g. building type).

A multizone model is representative of a specific building, so it is not unreasonable to view models as collections of building-specific information. Excluding all high-level information from the modeling process does not address the issue of making sure that high-level information is properly represented in the model. Manual verification of the properties of hundreds of model components is no small undertaking, so expert users tend to arrange tasks in ways that build the verification into the process. One technique specific to ContamW is to cut-and-paste icons of leakage paths so that all the paths that should be the same are the same. Beginning users or infrequent users of the software may lack the sophistication necessary to plan too far ahead, and thus may face hours of additional work that could have been avoided. Many of the common mistakes that less experienced users make can be prevented by building more expertise into the interface and preventing the beginner from following paths that will lead to problems. Collection and use of high-level information is one way for the modeling software to reduce the input requirements for new users. A streamlined process is not about making an overly simple or less functional model. It is about helping the user generate a model that is that is sufficiently representative of the building under study in less time and with less difficulty. In the following subsections, a number of specific streamlining opportunities are described. Some are quite small in scope, while others represent larger changes to the overall model creation.

Air Handling System Specification

It is often useful to specify air supply rates to zones on a per-square-foot basis (e.g. 1 scfm/ft^2) and a supply flow/return flow ratio as first-pass approximations. This short cut would not be acceptable in a highly detailed model, but can be acceptable in situations when the user is not certain of occupancy requirements or other details. CONTAM's simple air handling system feature is very compatible with this sort of specification, but it is not enough to simply allow the user to specify a supply/return ratio and per-area flow rates. These inputs must be maintained when other changes are made (e.g. a change in floor area) or simplification will be lost and the user will be burdened with manually verifying that all flow rates are correctly set. A simplified approach must store the user's input, detect changes that require updates of other parts of the model, and then reliably make the required changes.

Determine Wind Effects from High-Level Data

Wind effects are an important part of multizone airflow model, so proper specification of these effects is important. Ideally, measurements of wind pressure data would be available for use. This is not always the case, and CONTAM has flexible capabilities for specifying the effect of wind upon the building. The wind pressure P_w may be computed as

$$P_w = \frac{\rho V_{met}^2}{2} C_h f(\theta) , \qquad (2)$$

Where ρ is the ambient air density, V_{met} is the wind velocity measured at a local meteorological station, C_h is the wind speed modifier, and $f(\theta)$ is the wind pressure profile as a function of θ, which is the angle of the surface to the wind direction. The wind speed modifier, which adjusts the wind velocity to local conditions, is calculated as

$$C_h = A_o^2 \left(\frac{H}{H_{ref}} \right)^{2a} , \qquad (3)$$

where A_o is a terrain constant, a is a terrain exponent, H is the height at which wind pressure is calculated, and H_{ref} is the meteorological station height. These parameters may be specified individually or as part of an overall model. The terrain-related local shelter class from the model of Sherman and Grimsrud (1980) that describes local wind shielding conditions is one approach. A set of five shelter classes is provided, varying from no close obstructions to very close obstructions. The terrain constant and velocity profile exponent that are used to determine the wind speed multiplier are then available.

To streamline the selection of a wind pressure profile, the user is asked to describe the building as one of four building types: low rise, high rise with low aspect ratio, high rise with unity aspect ratio, or high rise with high aspect ratio. The aspect ratio is the ratio of the wind-parallel dimension of the building to the wind-normal dimension of the building. The wind pressure profile that should be used in the model depends upon the selected building type. For low rise buildings, the profile is taken from Swami and Chandra (1987) and for high rise buildings, the profiles are from Akins et al. (1979).

Automate Zone Creation

ContamW represents zones as enclosed areas in the sketchpad, but an enclosed area is not a zone until a zone icon is placed there. All enclosed areas must be defined as either an interior or ambient zone; otherwise, ContamW will flag the model as incomplete. Interior zones are much more common, so an obvious time-saving step is to automatically define all enclosed areas as interior zones and ask the user to redefine any ambient zones. Once zone icon placement is automated, it makes sense to collect or determine additional information on zones during the creation process, most notably zone size information. A new process to prompt the user to input wall lengths is introduced, in which the user is asked to sequentially input the lengths of walls. Once this is complete, the implementation may then detect rectangular zones that have equal length opposite sides. The volume of each zone identified in this manner is computed with the associated level height. Zones that are not selected in this process will still require manual input of the volume or floor area, the modeler may override the calculated area or volume should this be required, and wall length changes must be handled. The user is also asked to identify zones that require special treatment, such as elevator shafts and stairwells.

Building Leakage Characteristics

Rather than asking the user to specify leakage in detail (i.e. leakage path by leakage path) for each model component, an alternate approach is to specify leakage through most interior walls, floors, ceilings, and envelope components in terms of the expected leakage through the component as a whole. For example, a detailed approach would ask the user to individually account for each possible leakage path through a wall, while the alternate approach would base the expected leakage on the type of wall (e.g. interior or exterior) and an assessment of the leakiness of the wall. Large openings (e.g. doors that are always open) still must be accounted for, but an acceptable first approximation is to ask the modeler to make a judgment as to expected leakage level. Three options are defined as possible leakage levels: normal, tight, and leaky. The normal condition for exterior walls is the mean of all buildings summarized by Emmerich and Persily (2011) on a per-unit-area basis. The tight and leaky conditions are defined as ±1 standard deviation from the mean in the same survey, again for exterior walls. Interior walls are defined as having twice the airflow as the exterior walls under the same conditions. Similar relations hold for other wall or partition types. This operation frees the user from the burden of finding detailed information about the placement of building components that may lead to leakage airflows and ultimately frees the user from the task of placing most leakage paths (see below).

Automate Flow Path Creation

The typical ContamW process for creating the flow path connections between nodes involves the manual placement of each flow path icon. However, since the wall area that separates zones is now known along with the expected leakage rate, the next step is to assign leakage paths between neighboring zones

automatically. This frees the user from the manual placement and verification of each path, which greatly reduces the work necessary to create a model. Zones that have been previously identified for special treatment may be automatically handled as well. Elevator shafts and stairwells are one such example. For walls of elevator shafts and stairwells, the leakage rate is defined based upon an average of 15 buildings surveyed by Tamura and Shaw (1976) rather than on the regular interior wall leakage rate defined above. The interlevel leakage paths for elevator shaft zones and stairwell zones are defined using CONTAM's elevator shaft model and stair shaft model, respectively.

The placement of paths is a very important part of the modeling process, as the connectivity of the network determines what flows are possible. Mistakes in the placement of paths or in calculation and input of path parameters can lead to incorrect results. The streamlined process should still allow the user freedom in zone-to-zone connections (e.g. for open doors or windows), but repetitive path placement should be done automatically.

Provide a Reduced Set of Model Components

The CONTAM package is very flexible and allows for quite general model construction and for an effectively unlimited number of model elements. New users may have difficulty in choosing model elements when too many options are available. A smaller set to choose from simplifies matters, and even if the available elements have been ranked based upon other input (e.g. the leakiness of the building), the reduction in choice will benefit new users. A streamlined process should still allow the user access to a degree of customization of model components (as in ContamW), but the user should not be presented with many choices unless more choices have been explicitly requested.

Impose a Specified Order of Operations

ContamW allows users to construct models in nearly any order, which can lead to problems for inexperienced users. Poor planning can trap the user in a cascade of poor choices, ultimately resulting in the abandonment of the model. It is useful to encourage new users to follow a procedure that has been successfully used to develop many models in the past. The following process may be encouraged by placing menu items in a logical order and selective disabling of menu items that are not possible (e.g. automatic zone volume calculation cannot happen until after wall lengths are specified):

1. Walls are drawn
2. Wall lengths are specified
3. Zones are automatically assigned
4. Leakage airflow paths are automatically assigned
5. Air handling systems are constructed

This order of operations is recommended when using ContamW and it has produced a number of high-quality models that are suitable for use in calibrated model development.

RESULTS

A simplified version of the ContamW interface, called PCW, has been developed that implements the input streamlining techniques discussed above. To simplify the development task, the software was based upon the ContamW code, and many of the techniques used may be described as semi-automatic because the software partially automates the creation of certain parts of the airflow network based upon user input. PCW implements both graphical and parametric versions of the streamlined approach. An explicit goal in the development of the software was that input time per 10,000 square feet would be less than 1 hour. The attainment of this goal was tested with twelve timed model development exercises of the software with users of varying familiarity with CONTAM, including both novice users and experienced users.

Five prototype buildings were developed in order to test the effectiveness of the simplified model development process. These five buildings were selected to cover a variety of building sizes, system types, and levels of complexity, as described in Table 1.

Table 1 Prototype building models used in tests

MODEL	NUMBER OF LEVELS	TOTAL FLOOR AREA
Gymnasium	2	7980 ft^2
Dormitory	11	70,400 ft^2
House	2	1600 ft^2
Museum	5	13,925 m^2
Office	5	27,514 ft^2

The prototype buildings were supplied to users in the form of a building description comprised of a simplified floor plan, sufficient details to develop a simple air handling system model of the building mechanical system, and any other required information (e.g. occupancy for the study of CO_2 transport). These building descriptions were specifically designed to test a wide range of possible input options in order to identify as many program bugs and process shortcomings as possible. Each of the prototype buildings was modeled by at least one novice and one expert user using both PCW and ContamW.

The time required for model input using both programs was recorded and broken into steps so that the steps contributing most to input time could be identified. The

resulting project files and simulation results for PCW and CONTAMW were compared with expected results to determine differences between the two models and assess the model quality. Issues were identified either as program bugs and fixed or identified as user mistakes and recorded. Based on the results of this testing, a number of improvements were made to the program. These included bug fixes, as well as added features, including a feature to automatically calculate the building height used for wind modeling and improving the handling of supply point copy and paste operations.

Table 2 Per-user timing results (minutes/10,000 ft^2)

MODEL	PCW TIME (min/10k ft^2)	ContamW TIME (min/10k ft^2)	SPEEDUP
Gymnasium	35	128	3.66
Gymnasium	26	164	6.31
Dormitory	2	12	6.00
Dormitory	4	12	3.00
House	112	375	3.35
House	137	694	5.07
Museum	43	89	2.07
Museum	33	172	5.21
Office	42	94	2.24

Overall, the software met and exceeded the goals that were set for it in most of the test cases. For a building with a typical level of complexity, the PCW model input time was between 30 and 40 minutes per 10,000 square feet for both novice and expert users, exceeding the goal by a substantial margin. Table 2 provides a listing of the nine tests for which direct comparisons on a per-user basis is possible. For each test the development times using PCW and ContamW are given per 10,000 square feet, along with the speedup. The speedup is the ContamW time divided by the PCW time. The average speedup is 4.1, indicating that approximately 4 PCW models can be completed in the time required to complete a single ContamW model. This speedup corresponds to an approximately 75% reduction in model development time. The model input time only exceeded 1 hour per 10,000 square feet for the house prototype building, but this result is more related to the small size of the building than to shortcomings in the software or errors by the users. The small size of the house meant that the time required for overhead-type tasks that are not very dependent on building size dominated the total time required construct the entire model. This situation results in an increase in the time required per 10,000 square feet, but the time required to construct the model in PCW is still significantly less than that required using ContamW.

The tests showed that novice users benefit slightly more than expert users, likely due the fact that the PCW interface includes features specifically aimed at novice users. Expert users still benefit from using the interface, but the time savings is not as pronounced. The tool consistently allowed users to create project files in one-quarter to one-third the time required for ContamW. Comparison of the input files created using PCW and ContamW also showed that user input errors were reduced for both expert and novice users using PCW. The reduction was especially pronounced for novice users. Again, the novice users are benefitting from features explicitly intended to aid them in model development.

Subsequent use of PCW has shown that it can be used to speed up development of ContamW models that use functionality not supported by PCW. For example, PCW does not support the use of CONTAM's detailed duct HVAC models. To reduce the total time required to develop a model including this functionality, PCW is used to create zones and assign leakage flow paths. The resulting model is then loaded into ContamW and completed. The resulting time savings is typically not as large as in the timed tests (generally due to the complexity associated with the elements not supported by PCW), but is still sufficient to make the use of two modeling programs worthwhile.

Models developed with the PCW software have been successfully used by Bahnfleth et al. (2012) to produce calibrated airflow simulations. A parametric simulation technique is used to obtain a model that agrees with experimental measurements of building under controlled circumstances. The approach is found to be reasonably repeatable, and indicates that the models created with this streamlined approach are capable of representing real buildings. Further information on the software is available in this reference in the references therein.

CONCLUSION

The CONTAM multizone modeling package is an extremely powerful tool for the simulation of air transport processes in the indoor environment. Model development can require a significant investment of time and effort, and this tends to work against wider adoption of multizone modeling in practice. A number of techniques have been described that are aimed at decreasing the time and information required to construct a model that is reasonably representative of the building. These techniques are compatible with fully automatic model creation methods, but care must be exercised when pursuing such techniques. It is unlikely that fully automating model creation will be successful, as there issues that are difficult best handled by the user. In particular, automatic generation of a

sketchpad representation is difficult enough that it may be more efficient to construct this representation by hand with computer assistance rather than expect full computer construction.

A software implementation of these techniques has demonstrated that the time required to produce legitimate multizone models can be reduced by up to 75%. The resulting models have been used in a number of other projects very successfully, and work continues on further simplification of the multizone model development process.

The time savings realized in this effort are primarily in the form of a reduction of the required number of mouse clicks or key presses. The models produced here require less input information and the information-gathering step is easier, but there is still room for improvement. In some situations, the difficulty of gathering building information may be less of an issue in the future (e.g. BIM data is available), but this does not reduce the value of easy-to-use, validated modeling software. PCW is not yet as user-friendly as desired, still requires too much expertise, and is limited to the Microsoft Windows platform. A cross-platform, more flexible implementation is under development.

ACKNOWLEDGMENT

REFERENCES

Akins, R., Peterka, J., Cermak, J. 1979. Averaged pressure coefficients for rectangular buildings, Wind Engineering. Proceedings of the Fifth International Conference 7:369-80. Fort Collins, CO. Pergamon Press, NY

Axley, J., Grot, R. 1989. The Coupled Airflow and Thermal Analysis Problem in Building Airflow System Simulation, ASHRAE Transactions 95, Part 2, p. 621-628.

Bahnfleth, W., Saekow, P., Firrantello, J., Kremer, P. 2012. Comparison of semi-quantitative and formal metrics for multi-zone airflow model quality assessment, HVAC&R Research, 18(1-2):252-263.

Basarkar, M., Swami, M. 2006. IFC to CONTAM Translator, SimBuild 2006, Boston, MA.

DeGraw, J. W., Bahnfleth W. 2011. Quantifying Chemical/Biological Event Severity with Vulnerability-Based Performance Metrics. ASHRAE Transactions, 117(1), 282-289.

Dols, W. S., Matzke, B. D., Sego, L. H., Morrow, J. B., Nuffer, L. L., Pulsipher, B. A., Persily, A. K. 2009. Development and Demonstration of a Method to Evaluate Bio-Sampling Strategies using Building Simulation and Sample Planning Software, NIST Technical Note 1636.

Feustel, H. E., Rayner-Hooson, A. (Eds) 1990. COMIS Fundamentals, Lawrence Berkeley Laboratory, Report LBL-28560.

Emmerich, S.J., Persily, A.K. 2011. U.S. Commercial Building Airtightness Requirements and Measurements. AIVC Conference 2011, Brussels, Belgium.

Sherman, M., Grimsrud, D. 1980. Infiltration-pressurization correlation: Simplified physical modeling, AHSRAE Transactions 86, Part 2, p. 778-807.

Swami, H., Chandra, S. 1987. Procedures for calculating natural ventilation airflow rates in buildings, Final Report FSEC-CR-163-86, Florida Solar Energy Center, Cape Canaveral.

Tamura, G., Shaw, C. 1976. Air Leakage Data for the Design of Elevator and Stair Shaft Pressurization Systems, ASHRAE Transactions 82, Part 2 p.54-71

Walton, G. N.1982. Airflow and Multiroom Thermal Analysis. ASHRAE Transactions 88, Part 2, p. 78-91.

Walton, G. N., Dols, W. S. 2010. CONTAM User Guide and Program Documentation, NISTIR 7251.

Wetter, M. 2006. Multizone Airflow Model in Modelica. Proc. of the 5th International Modelica Conference, Vienna, Austria. p. 411-440.