COMPUTATIONAL AIR FLOW MODELING FOR INTEGRATIVE BUILDING DESIGN

Wong Nyuk Hien, National University of Singapore, Singapore 117592
Ardeshir Mahdavi, Carnegie Mellon University, Pittsburgh PA 15213,USA

ABSTRACT

The use of air flow modeling tools for building design is still limited due to lack of explicit standards governing infiltration and ventilation rates in buildings. There is also inconsistency and discrepancy in the use of such modeling tools throughout the entire design process. Lack of integration of the tools with architectural design environments as well as with other performance simulation tools further hamper their use. This article discusses the development of a computational air flow model (BACH) which could be used consistently throughout the entire design process and its integration within a computational design environment (SEMPER).

INTRODUCTION

The current research on air flow modeling and their integration with design tools still falls short of effectively supporting simulation-based architectural design decision-making. Analysis of air flows is still significantly lagged behind modeling of other building features because of limited data, computational difficulties and incompatible methods for analyzing different flows [Walton 1989]. Currently there are very few explicit standards which are used for the computation of infiltration and ventilation rates. There is inconsistency and discrepancy in the use of such tools throughout the entire design process. The tools that have been developed to support early design rely mainly on empirical methods where the accuracy of the computation is based on the availability as well as accuracy of the data. On the other hand, the use of advanced CFD tools often result in the discrepancy between early design requirements and the very detailed and cumbersome features of the advanced CFD tools. Lack of integration of air flow modeling tools with architectural design environments also hamper their use within the design process. Conventional CAD tools do not typically offer comprehensive geometric information for such simulations. There is also lack of integration of air flow models with other performance simulation tools such as thermal and HVAC simulations. As such, data pertaining to these domains are usually assumed to be constant which will result in inaccuracy in the simulations.

With respect to the status and limitations of the current air flow modeling tools as discussed, this paper describes the development of a computational air flow model (BACH) which aims to address the above issues. BACH was implemented following the two underlying premises of being “consistently first principles based” and “designer friendly”. Thus, it has the flexibility to simulate air flows in buildings consistently throughout the entire design process. It describes the capability of BACH to deal with complex building designs, particularly buildings with non-orthogonal geometries by utilizing a research tool (GRAIL) for solid modeling [Stouffs 1994], and augment it with additional procedures to enable the treatment of complex building designs. It also demonstrates the integration of BACH and SEMPER [Mahdavi et al. 1996a] by illustrating with the use of homology-based mapping, how multiple application-specific representations could be generated from a shared, space based CAD system and the dynamic linkages of BACH and the various simulation modules in SEMPER, thus allowing concurrent multi-domain performance evaluations.

THE AIR FLOW MODEL IN BACH

Overview of BACH

BACH (Building Air Change) can be characterized as following a hybrid multi-zone and CFD approach. It allows 3-dimensional analysis of air flow and contaminant dispersal. It takes into consideration the effects of wind, temperature difference and mechanical ventilation. It computes the air change rate for each space and provides a visual display of the air flow profile. A small database which captures the infiltration characteristics of window and door openings is incorporated to account for the effects of infiltration. With the use of weather file, it allows hourly simulation taking into consideration the effects of opening schedule. It also incorporates a simple gaseous contaminant dispersal model which provides steady, transient and cyclical contaminant dispersal analysis.

Network Structure

Figure 1 shows the network structure of BACH for a building with orthogonal geometries. The simulation domain can be discretized into a network consisting of nodes that represent regions of differing pressures interconnected by linkage paths. The network is numerically described by a system of equations formed by applying an appropriate flow equation to each path. These equations are solved by determining the pressure distribution such that a mass flow balance is preserved for each node. To simulate boundary conditions such as the building envelope, the linkage paths joining nodes inside and outside the building envelope are adjusted accordingly. Flow paths due to cracks and openings are governed by the sizes of these linkage paths. The same principle applies to internal partition, where the linkage paths joining the nodes adjacent to the partition are disconnected accordingly.

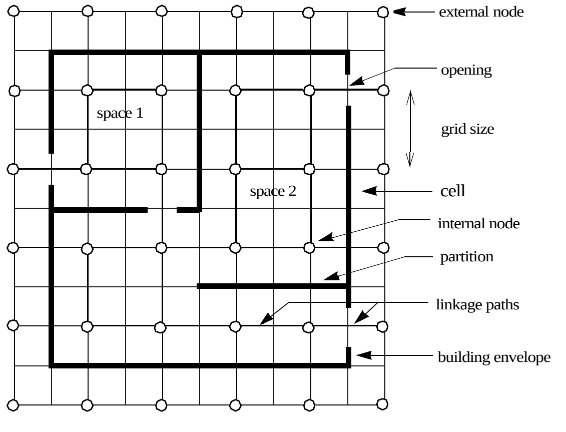


Figure 1: General schema for grid, network structure and space layout for BACH

Overview of Algorithms

The Flow Equation

The flow rate $\dot{V}$ is expressed in terms of pressure difference by this generic equation:

$$\dot{V} = K \cdot (\Delta P)^n$$

where

$\dot{V}$ air flow rate [$m^3.s^{-1}$]
ΔP pressure difference across the pipe [Pa]
K flow coefficient [$m^3.s^{-1}.Pa^{-1}$]
n flow exponent

Simulation of Wind Effects

One of the most difficult problem encountered in the use of multi-zone network model is the establishment of the dynamic pressure on the building envelope due to wind. Most of the models (e.g. CONTAM94) require the user to input the values of pressure coefficient (C_p) at the location of the flow path. This could be difficult since the C_p values are largely governed by factors such as wind velocities and directions, architectural as well as environmental conditions. In most cases, the C_p values have to be obtained empirically either by field measurements or wind tunnel tests. As a result, the wall averaged C_p values have to be used for the computation. However, such wall averaged values of C_p usually do not match the accuracy required for multi-zone air flow models.

In this model, by extending the domain to include external air flow, the network eliminates the need to input the values of C_p for each flow path or the development of a separate module for the computation of C_p (e.g. COMIS). Instead, the boundary conditions for the external air flow, which include the wind velocity and its angle as well as the profile are specified. This approach can also consider the effects of surrounding buildings and obstructions.

The time-mean wind speed profile can be determined using the following expression:

$$v = v_r \cdot c \cdot H^a$$

where

v mean wind speed at height H above the ground [$m.s^{-1}$]
v_r mean wind speed measured at a weather station at a height 10 m above ground [$m.s^{-1}$]
c, a terrain factors

Simulation of Stack Effects

The pressure difference due to the thermal buoyancy :

$$P_s = \rho_o \cdot g \cdot 273 \cdot \left[\frac{1}{T_2} - \frac{1}{T_1}\right] \cdot [h_2 - h_1]$$

where

P_s stack induced pressure at level h_2 with respect to an opening at level h_1 [Pa]
g acceleration due to gravity [$m.s^{-2}$]
ρ_o density of air at 273 K [$kg.m^{-3}$]
T_2 temperature at node 2 [K]
T_1 temperature at node 1 [K]

Simulation of HVAC Effects

The description of the air jet generated by a HVAC diffuser could be mathematically very complex [Awbi 1991]. This model does not intend to fully describe this flow phenomenon. As such, the HVAC ventilation supply and return are described as fixed flow rates, i.e. they act as source and sink in the computation. In SEMPER, these data are obtained dynamically from HVAC simulation module.

Contaminant Analysis

The contaminant dispersal model in BACH follows very closely the approach used by CONTAM94 [Walton 1989]. However, since a zone can be represented by multiple nodes, the concentration of the pollutant in this case is computed based on each node.

The concentration of the pollutant at node i at time t:

$$C^*_{\alpha,i} = \frac{\left[m_i \cdot C_{\alpha,i} + \left(G_{\alpha,i} + \sum_j (w_{j,i} \cdot C^*_{\alpha,j}) \right) \cdot \Delta t \right]}{\left[m_i + \Delta t \cdot \sum_i w_{i,j} \right]}$$

At steady state, the concentration of pollutant at node i:

$$C_{\alpha,i} = \frac{\left[G_{\alpha,i} + \sum_j (w_{j,i} \cdot C_{\alpha,j}) \right]}{\sum_i w_{i,j}}$$

where

m_i	mass of air in node i [kg]
$C_{\alpha,i}$	concentration mass fraction α $[kg_\alpha \cdot kg_{air}^{-1}]$
$\sum_j (w_{j,i} \cdot C_{\alpha,j})$	inward air flow rate from nodes j to node i [kg.s^{-1}]
$G_{\alpha,i}$	contaminant generation rate $[kg_\alpha \cdot s^{-1}]$
Δt	time interval [s]
*	a value at time t + Δt

The functionality of this contaminant dispersal model will be illustrated in case study 1.

INTEGRATION OF BACH WITH SEMPER

The desired integration of detailed simulation methods and CAD systems is complicated by the fact that the building representation used in commercially available CAD systems do not adequately match the building representation needed for detailed simulation methods. For example, in the case of air flow simulation, detailed simulation requires the definition of spaces and not just bounding surfaces. Furthermore, such representations must allow for conducting domain-relevant operations such as spatial discretization, grid generation, finite control volume definition etc. Evidently, conventional CAD tools do not satisfy either of these conditions. Consequently, in order to integrate a detailed simulation tool with such CAD system, mechanisms like geometry interpretation (which are inherently brittle and unscaleable) would have to be used. On the other hand, a semantically enriched space-based CAD system would provide a representation that is practically homologous to that needed for a detailed air flow simulation, and thereby facilitate integration more effectively and reliably. Here, the term "homologous" is used to mean that the two representations have information structured in a manner such that they can be derived from each other without having to interpret semantics (e.g. geometry interpretation).

In the SEMPER environment, the building design representation (BDR) embodies topological information and it therefore has “knowledge” of architectural spaces and their relationships (adjacencies etc.). The underlying simulation domain representation (SDR) in BACH is configurationally homologous to the building design representation (BDR) in the shared object model, and can therefore be directly (and unambiguously) derived from it [Mahdavi et al. 1997a, Mahdavi and Wong 1997b]. This homologous mapping between representational and analytical building object models thus provide “one-line” simulation feedback to the user while eliminating the need for explicit definition and updating of the underlying simulation modules. Furthermore, this is done without having to use complex application-specific translators or communication frameworks. With homology-based mapping, it is possible to have multiple application-specific representations generated automatically from a shared, space-based CAD system. The above concept can be illustrated for the thermal analysis and air flow simulation modules in SEMPER.

Consider for example the sequence as shown in figure 2, in which the geometric manipulation of an initial design scheme (e.g. addition, deletion, or resizing of spaces) is automatically mapped into an updated nodal configuration in the simulation modules. As spaces are added to the initial scheme, the modules create the cell nodes for the new space, and automatically update the boundary conditions for the wall nodes. For the thermal analysis module, the wall nodes are updated to reflect the internal walls between the two spaces. For the air flow simulation module, the linkage path linking the adjacent nodes is disconnected to reflect the presence of an internal wall/partition. In the presence of a door/window, the linkage path reconnects the two adjacent nodes.

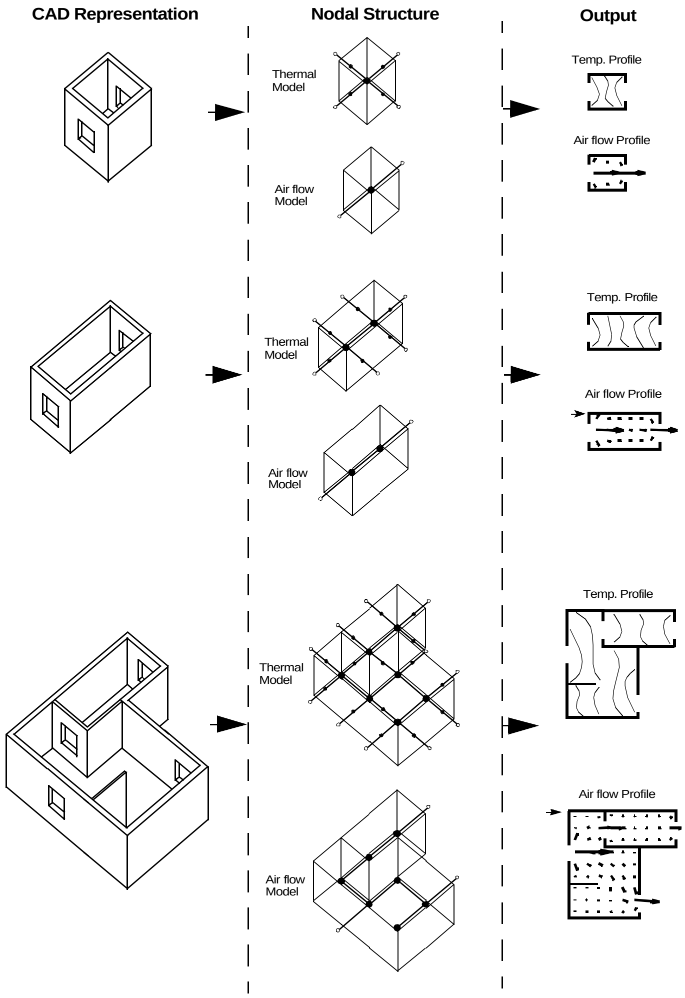


Figure 2: Homology-based Mapping for multi-domain simulations [Mahdavi et al 1997a]

Through all the steps of the sequence, both the thermal node configuration and the nodal network for air flow simulation are automatically updated based on design modification in the shared object model. The user is thereby able to manipulate a design using a representation familiar to him/her, and concurrently perform detailed performance simulations without any additional intervention or manipulation of the application-specific representations.

In SEMPER, direct links between individual domain applications are avoided. Instead, the links occur at the object model level through mechanisms such as derived values, allowing for individual application to be developed fairly independently, while still communicating in an effective manner.

TREATMENT OF COMPLEX BUILDING GEOMETRIES

In SEMPER's first prototype, the geometry of architectural spaces was captured in terms of extruded orthogonal polygons. The spaces were discretized in terms of a set of spatial (3-dimensional) grid elements (cells). As long as the spaces were constructed following this spatial grid system, the SDR could be derived from the geometric information in BDR. The use of a nodal system in this scenario is confined to buildings with orthogonal geometries. Thus, the effects of sloped surfaces such as pitched roofs or walls tilting at an angle cannot be modeled. This limits the applicability of the simulation engine for a consistent first-principles-based modeling of the performance of a relatively large number of buildings, from simple single houses and passive solar designs to geometrically adventurous (e.g. deconstructivist) statements in design.

It is conceivable that one could deal with non-orthogonal spatial grid structure. However, this option was not adopted since the major advantage of the orthogonal grid structure lies in the way it facilitates the automated formulation of matrices needed for numeric computations in various performance simulation domains. It was, thus, essential to develop a scheme which would allow the treatment of non-orthogonal geometries while retaining the computationally decisive benefits of an orthogonal spatial grid structure for the organization of finite control volumes and nodes [Mahdavi and Wong 1997b].

To solve this problem, geometric reasoning operations are needed to identify the "interface" or cross-section between complex (non-orthogonal volumes) and an orthogonal grid structure. As conventional CAD tools do not typically offer the type and range of such geometric reasoning operations, a research tool (GRAIL) for solid geometry modeling [Stouffs 1994] is used and augment it with additional procedures to enable the treatment of complex building designs in the SEMPER environment. The essential idea was to use indoor-outdoor node couples as the starting point. Once such couples are identified, the two cells associated with this node couple can be merged to create an expletory transient double cell volume. The intersection of these expletory volumes with the spaces of BDR allow for the derivation of the necessary geometric attributes (shape, area, tilt, etc.) of enclosure elements of the building's spaces.

Figure 3 illustrates the process of generating a nodal representation for a space of non-orthogonal geometry, conforming to a 3-dimensional orthogonal spatial grid structure.

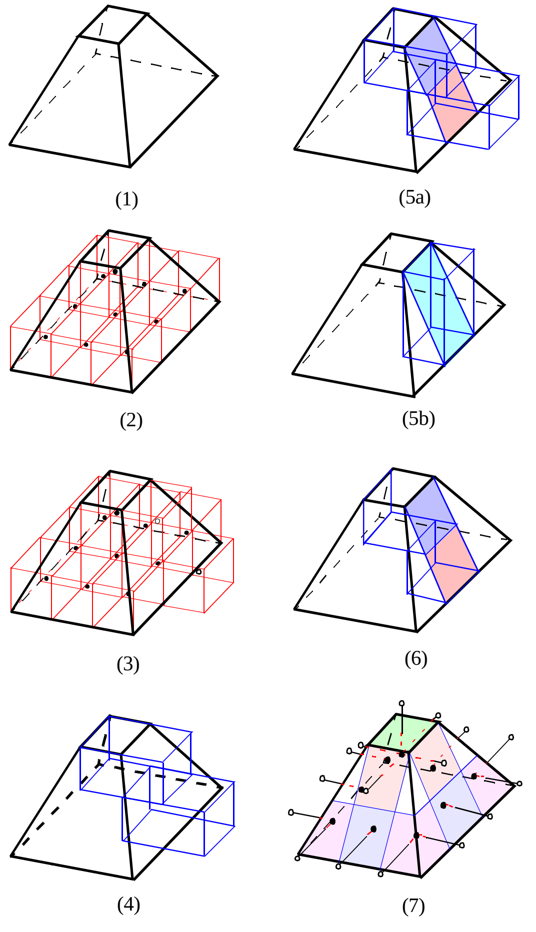


Figure 3 :Generation of nodal presentation for a space of pyramid shape

DEMONSTRATIVE CASE STUDIES

Case 1: Single Story Building with Orthogonal Geometries

Figure 4 shows the schematic plan of the test case, which is a single story house with orthogonal geometries. The house was assumed to be located at city area.

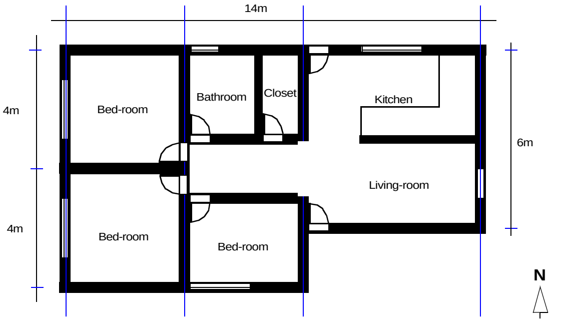
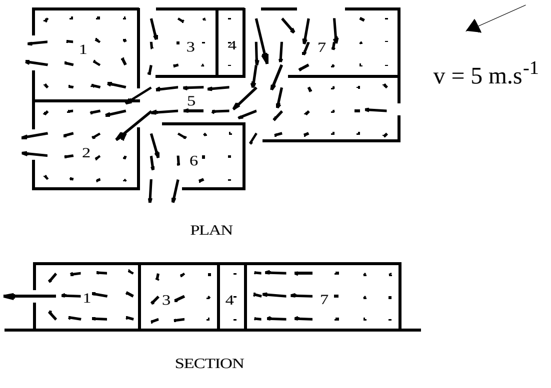


Figure 4: Schematic layout of the test case

The simulation was carried out using a grid size of 1 m and all the external openings were assumed fully closed and thus the air change was solely due to the infiltration through the leakages at these external openings. The wind speed was 5 $m.s^{-1}$ flowing from North-East direction (125^o). Figure 5 shows the air flow profile as well as the air change rate of each space for the test case.



Space	Space Volume (m^3)	Volume Flow ($m^3.s^{-1}$)	Air Change Rate (ACH)
1	48	0.0016	0.1178
2	48	0.0020	0.1478
3	27	0.0014	0.1902
4	9	0.0000	0.0000
5	24	0.0064	0.9669
6	36	0.0031	0.3079
7	108	0.0104	0.3458

Figure 5:Air flow profile and air change rate for each space

With the use of weather file, BACH can also generate an hourly report of air change rate for each space. Figure 6 shows the hourly report of the air change rate for each space for the month of February using the Pittsburgh weather.

BACH has also incorporated a simple contaminant dispersal algorithm which computes contaminant concentration in each space and allows for steady, transient and cyclical state contaminant analysis. In the simulation, the contaminant source was located at space 7 with a source strength of 10 $mg.s^{-1}$. The simulation was carried out using the same boundary conditions, i.e. with all external openings fully closed and a wind speed of 5 $m.s^{-1}$ flowing from North-East (125^{o}) direction. Figure 7 shows the contaminant concentration for each space over time.

Case 2: Casa Macabre

To demonstrate the SEMPER-BACH's capability to simulate building with complex geometries, a test case Casa Macabre was used [Mahdavi and Wong 1997b]. The design although catastrophic in aesthetic terms, represents a good case in point and a formidable challenge for any integrated geometric reasoning and performance simulation system. Casa Macabre has namely complex spaces with non-orthogonal bounding surfaces. It also involves tilted roof surfaces as well as a void (a courtyard-like space) within the overall building volume (figure 8).

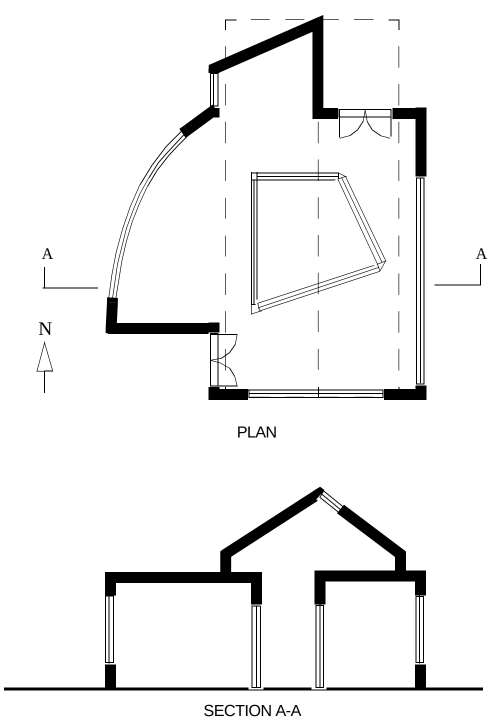


Figure 8: Schematic plan and section view of the demonstrative Casa Macabre

Figure 9 shows illustrative examples of the internal and external air flow profiles due to wind pressure and stack effect for the various opening configurations.

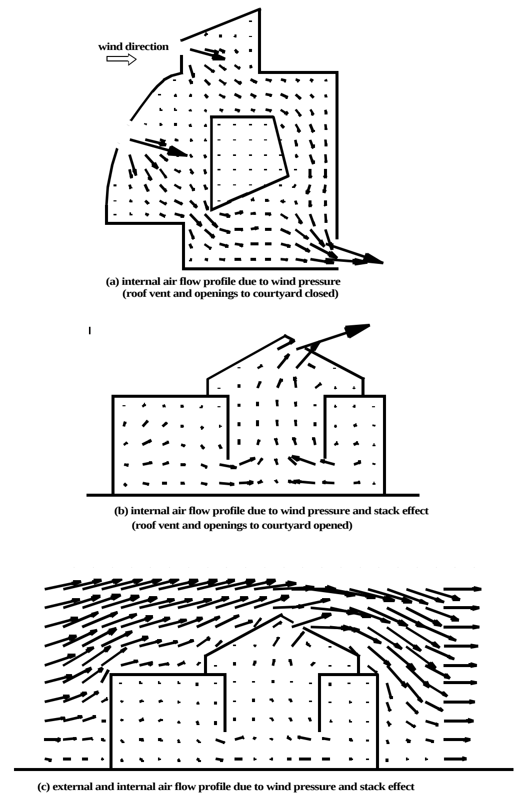


Figure 9: Internal and external air flow profiles in Casa Macabre as computed by BACH

CLOSING REMARKS

The research effort described in this paper has demonstrated the development of a computational air flow model (BACH) with the quest towards the development of an active, integrated design and performance simulation environment (SEMPER). By adopting a hybrid and CFD approach, it has certain advantages over the current multi-zone network models. They include:

- *The coupling of internal air flow with external air flow*

  Currently, most air flow models require the user to input the values of pressure coefficient (C_p) for each flow path. The published data is usually in the form of wall averaged values, which does not match the accuracy required. The use of statistical regression analysis requires the development of separate computational modules and the necessary linkage with the air flow model. The coupling eliminates the above problem.

- *The use of multi-cells for each zone/space in the building*

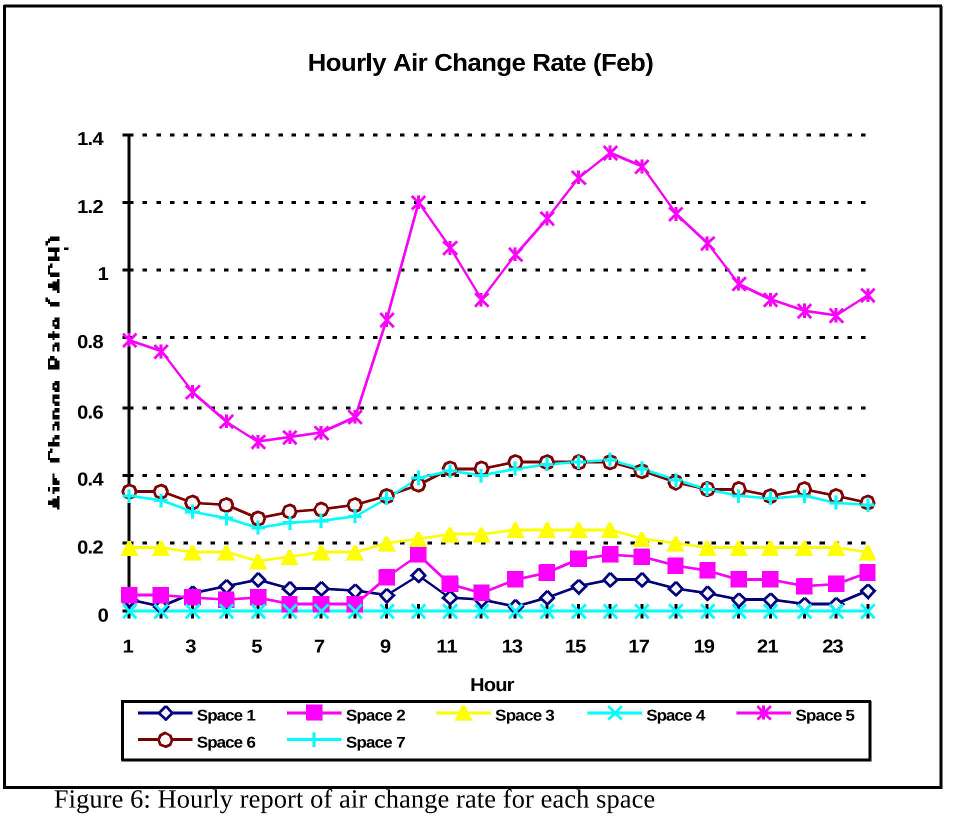


Figure 6: Hourly report of air change rate for each space

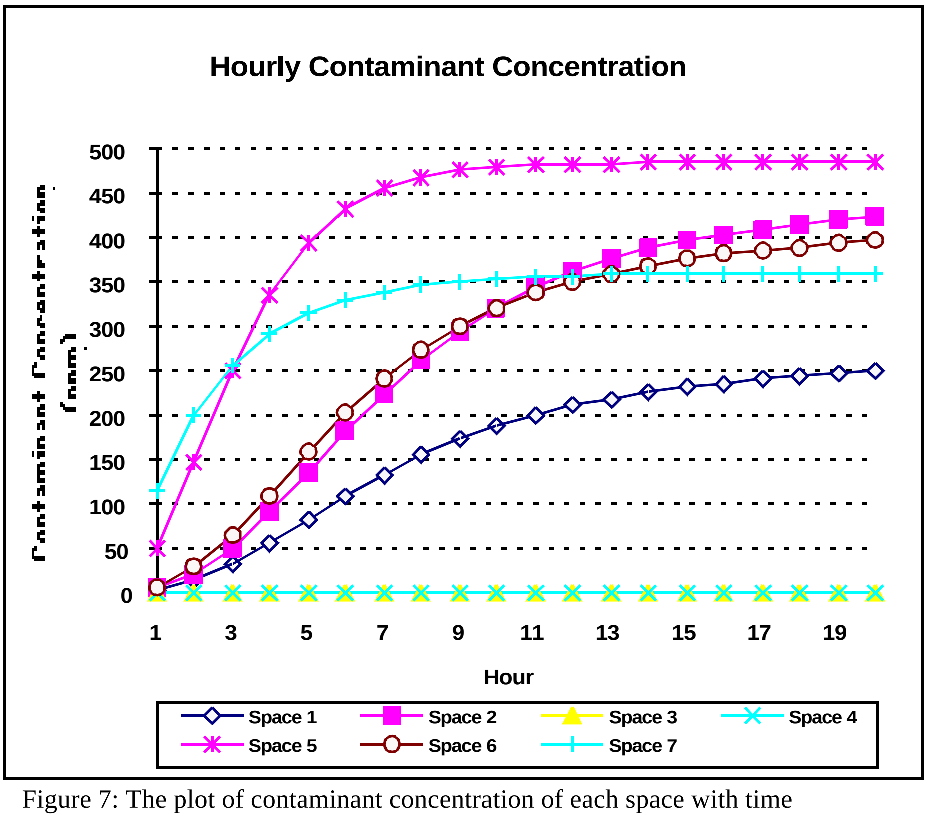


Figure 7: The plot of contaminant concentration of each space with time

This approach takes into consideration the effect of incomplete mixing of air within each space/ zone of a building since each space consists of multiple cells. This is especially important for buildings with large internal space configurations such as churches and auditoriums. The impact of internal partitions as well as other objects could also be modeled.

- *The use of control volume allows the visualization of the air flow profile and contaminant dispersal within the multi-zones of the building*
- *Treatment of complex building geometries*
  This paper illustrated the procedure of generating non-orthogonal geometries in buildings for air flow simulations. This is achieved by adopting a research tool (GRAIL) for solid modeling and augment it with additional procedures to enable the treatment of complex building designs.

During the development of BACH, a simplified CFD approach was adopted to extend the capability of the existing multi-zone network model. The main intention was to minimize the computational resources of the simulation engine as well as to make the boundary conditions as transparent to the user as possible. However, such simplification also results in the failure of the model to fully capture the air flow effects. Thus the major areas in which the air flow modeling capacity in BACH are extending include:

- *Incorporation of momentum and turbulent effects*
  Currently the air flow effects are governed mainly the pressure difference between the adjoining nodes. Due to this simplification, the momentum and turbulent effects are not captured. It is therefore important that such effects should be incorporated. However, the incorporation should not result in a drastic increase in the computational complexity and resources.
- *Simulation of boundary conditions for external flow around the building*
  The model has simulated the external flow by coupling the external with internal nodes. The comparison of Cp values generated by the simulation and that obtained from wind tunnel and CFD has matched well for a square building with various wind angles except at the edges.However, the air flows around a building can be very complicated and this more comparisons and extension have to be carried out.

REFERENCES

Awbi, H.B. (1991): Ventilation of Buildings, London, Spon

Grosso, M. (1992): Wind Pressure Distribution Around Buildings: a Parametrical Model, Energy and Buildings, Vol 18, 1992

Mahdavi, A. - Mathew, P. - Lee, S. - Rohini, B. - Chang, S. - Kumar, S. - Liu, G. - Ries, R. - Wong, N.H. (1996a): On the Structure and Elements of SEMPER, Proceedings of the 1996 ACADIA conference. Tuscon, Arizona. pp 71-84

Mahdavi, A., V.Loftness, P.Mathew, R. Brahme, S. Kumar, N.H. Wong. (1996b): Integrated Modeling of the thermal Environment, Proceedings of the 1996 International Symposium of CIB W67 (Energy and Mass Flows in the Life Cycle of Buildings). Vienna, Austria. pp 561-566.

Mahdavi, A. - Mathew, P. - Wong, N. H. (1997a): A Homology-based Mapping Approach to Concurrent Multi-domain Performance Evaluation, Proceedings of the The Second Conference on Computer Aided Architectural Design Research in Asia: CAADRIA '97 (Ed.: Yu-Tung Liu, Jin-Yen Tsou, June-Hao Hou). Hsinchu, Taiwan. pp. 237 - 246.

Mahdavi, A., N.H. Wong. (1997b): From Building Design Representations to Simulation Domain Representations: An Automated Mapping Solution for Complex Geometries, in Proceedings of the International Computing Congress held in conjunction with 1998 ASCE Annual Convention & Exhibition. October 18-21, 1998, Boston. American Society of Civil Engineers, pp 1-10

Stouffs, R. (1994): The Algebra of Shapes, Ph.D. thesis. School of Architecture, Carnegie Mellon University, Pittsburgh, PA.

Walton, G.N. (1989): Airflow Network Models for Element-based Building airflow Modeling” ASHRAE Transactions, 1989.