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COMPLEX BUILDING PERFORMANCE ANALYSIS IN EARLY STAGES OF DESIGN:

A solution based on differential modeling, homology-based mapping, and generative design agents

R. Brahme[1], A. Mahdavi[1,2], K.P. Lam[3], S. Gupta[1,3]

[1]School of Architecture, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[2]School of Design and Environment, National University of Singapore, Singapore 17566

[3]Dept. of Building, School of Design and Environment, National University of Singapore, Singapore 17566

ABSTRACT

Computational performance-based building design support faces a conflict. It is important to provide building performance feed back to the designer as early as possible in the design process. But many aspects of building performance are significantly affected by the design of the building's technical systems, which are typically configured in detail only in the later stages of design. The challenge is thus finding a method to use detailed simulation tools even during the early stages of design when values for many of the variables for the building's technical sub-systems are not yet available. In this paper, we offer a solution that involves differential modeling, homology-based mapping, and generative design agents. To demonstrate the feasibility of the proposed solution, we conclude the paper with illustrative examples of detailed performance analysis of complex buildings and their systems, in the early stages of design.

INTRODUCTION

Certain levels of building performance analysis are more relevant to the types of questions that need to be asked and answered by primary building designers (particularly architects). These include decisions pertaining to the effects of enclosure and glazing, massing, orientation, natural ventilation. Analysis of detailed building technical sub-systems may be more relevant to the activities of the domain specialist (e.g., lighting, energy systems). However, many aspects of building performance are significantly affected by the design of the building's sub-systems, such as distributed vs. central HVAC (heating, ventilating, and air-conditioning) systems. The question then, in the context of the building performance analysis tools, is how to provide performance feed-back to the designer as early as possible in the design process, while considering the technical sub-systems as well. The challenge is thus to find a method to use detailed simulation tools even during the early stages of design when values for many of the variables for the building's sub-systems are not yet available. Such a method could help in reducing the input data and thus make the usage of the tool easy for a general user (for instance, the primary building designer versus a user who is an expert in energy systems).

This problem can be partially solved by providing a differential building representation that allows automated mapping and generative design agents:

Differential building representation

The idea is to map the building's topological information in a shared building representation into the domain representation automatically. As a case in point, the domain representation for the HVAC sub-system is considered in this paper.

Technical sub-system design agent

The generative agent for the design of the HVAC sub-system is illustrated. It allows the user to analyze a complete HVAC system using detailed algorithms, while working with a minimum amount of input information. A method that automatically generates the distribution network for HVAC systems with minimal inputs from the user is described.

DIFFERENTIAL BUILDING REPRESENTATION

Building performance analysis can be performed at various levels of depth and resolution. A building model that is too restricted, may allow only for a limited and ultimately less useful set of analysis options. On the other hand, a model that would capture all the requirements of technical sub-system analysis may become too large, leading to the classic problems of massive product models (Mahdavi et al. 1999). To address this issue, we use a differential building representation approach adopted by the SEMPER (Mahdavi 1999) and S-2 (Mahdavi et al. 1999) efforts. This approach distinguishes between a general building representation and various building representations for a number of technical disciplines.

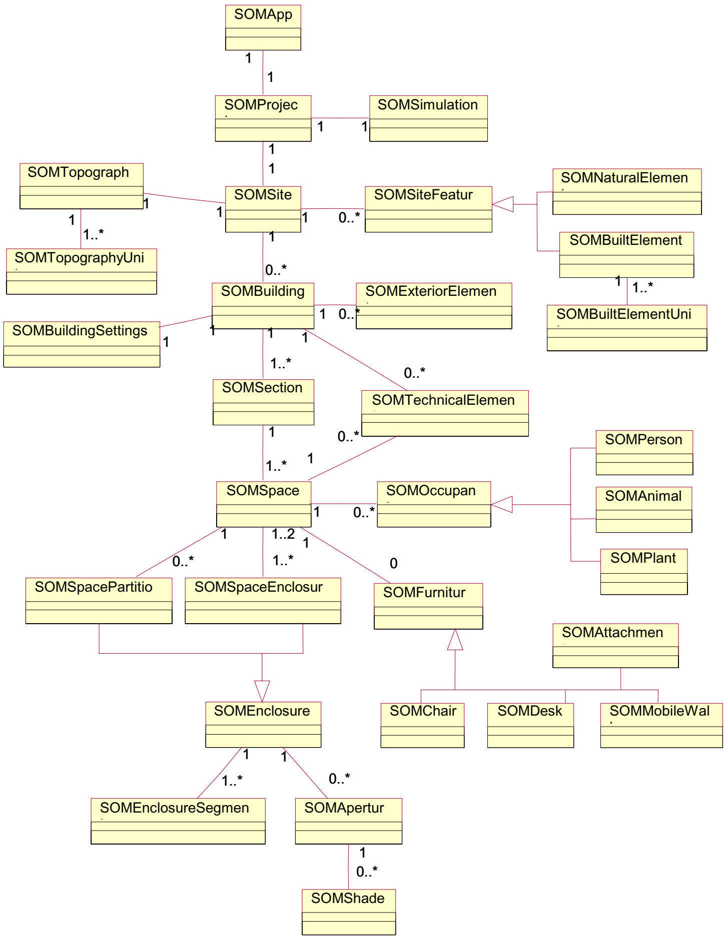


Figure 1: Shared Object Model (Primary Physical Elements)

The general building representation (SOM - shared object model) incorporates most of the information needed for the configurational definition of the building early in the design process, and responds to the informational requirements of the core analysis capabilities of a building design tool. Figure 1 shows the SOM. It reflects a building representation that is transparent to building designers. The domain object models for each of the applications are derivable from the SOM without any user intervention (Mahdavi et al. 1997). It also incorporates some basic information for the various technical sub-systems to facilitate a second automated operation. In case of the HVAC sub-system, this consists of minimal information - the system type and location (to decide if it is a pipe or duct network and its starting point) and the location of the distribution network (ceiling or floor). Such information is readily available even during the early stages of design.

The detailed information on the building's technical sub-systems is captured in various disciplinary representations (DOMs - domain object models). Figure 2 shows the DOM for the HVAC sub-system. The highlighted boxes show the information that is automatically mapped from the SOM. The HVAC simulation module utilizes a spatial representation consisting of spatial units (cells) with nodes that define finite control volumes (Figure 3). The nodal representation of the building is configurationally homologous to the space-based building representation in the SOM and is automatically derivable from it. This homology-based mapping mechanism allows for rapid feedback and is therefore a powerful design support instrument, since evolving building designs can be made subject to comprehensive parametric studies in multiple domains without having to input the building model separately for each domain (Mahdavi and Wong 1998, Mahdavi et al. 1997).

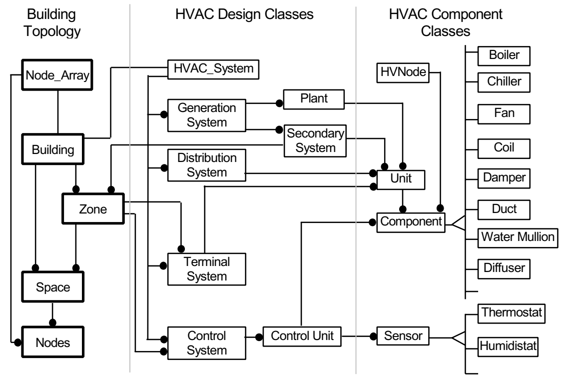


Figure 2: Domain Object Model forHVAC sub-system

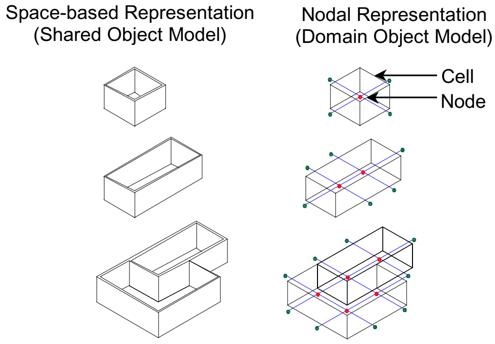
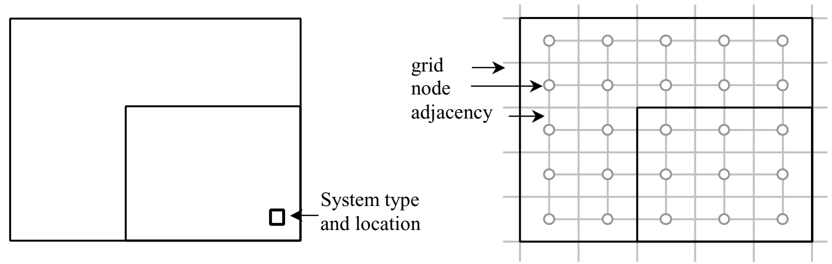


Figure 3: Homology-based mapping

TECHNICAL SUB-SYSTEM DESIGN AGENT

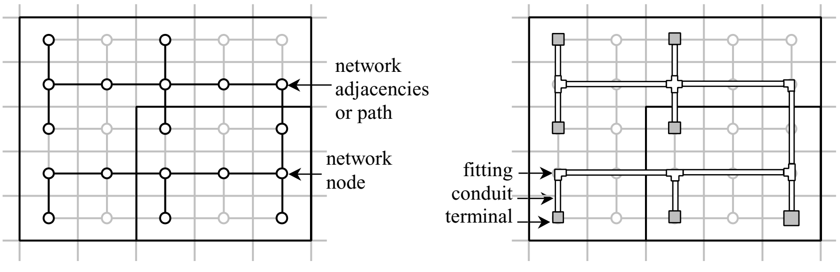
A first homology-based automated mapping operation allows for the derivation of a basic DOM from SOM. However, to perform computational building performance analysis, a complete DOM is required. In case of the HVAC DOM, a full description for the HVAC design classes and the component classes is required to allow for a complete performance analysis. Further detailed technical information to complete the DOM is typically provided by the user. To do this without user intervention, a second automated operation is needed (from the initial DOM to a complete DOM). To accomplish this, we adapt a technical sub-system design agent approach. In case of the HVAC sub-system, once the building design classes are obtained by the first mapping process (Figure 4b), the remaining information needed to complete the HVAC DOM is generated automatically by using a generative design agent.

Briefly, the design agent uses the system type information to configure the generation components of the HVAC system. It uses heuristics to design the terminal system and a combination of heuristics and shortest-path algorithm to design the distribution system components (Figure 4c and d). Once the system design is complete, all components are sized automatically. These components are represented as nodes and their adjacencies with other components (or with boundary conditions) are represented as paths. The nodes and the paths make up the complete HVAC system network which is numerically described by a system of equations formed by applying appropriate flow and energy equations to each node/path. Finally, the performance of the system (e.g., energy consumption) is computed automatically at each time step, for the specified time frame.



a) Building input

b) Building nodes – 1st mapping process



c) Layout Nodes – 2nd mapping process

d) HVAC Components – 2nd mapping process

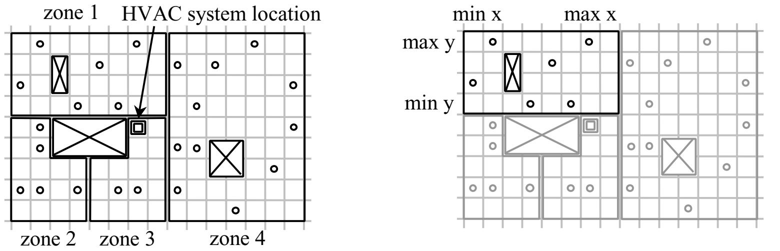
Figure 4: General scheme for grids, nodes and component network structure

Distribution System Design

Distribution system conveys a heating or cooling medium from the generator location to the portion of a building that requires conditioning. It is highly unlikely that the primary building designer (typically the architect) would model different system configurations (central vs. distributed, floor-based vs. ceiling-based, ducted vs. plenum etc.) to see their effect on energy consumption, if the network has to be input manually for each configuration. An automatically designed network would thus be useful in evaluating such alternatives, especially at the initial design phase.

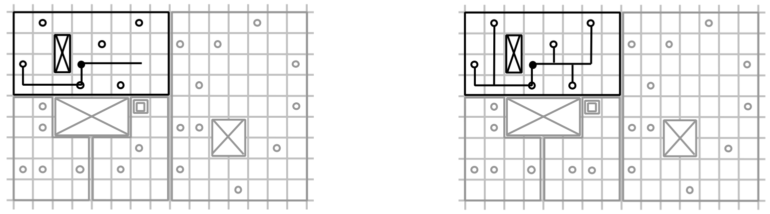
The generative design agent responsible for the automatic generation of the distribution network uses a combination of heuristics and shortest-path algorithm. The input for the design agent is the building geometry, location and type of HVAC system and the location of the distribution network (whether it is floor based or ceiling based). This information is captured in the SOM and automatically mapped to the DOM in the first mapping operation. Before we proceed into the description of the second automated process, i.e. the underlying rules and algorithms for generating the distribution network, a definition of the terminology is offered below:

- *Zone: Group of architectural spaces in a building which are controlled by the same controller.*
- *Cluster: A region in a zone encompassing all the terminals located within a certain range.*
- *Branch: A branch is a duct or pipe section that allows fluid flow from one point to another.*
- *Secondary system: Secondary systems serve one or more sections of the building. They consist of prime movers (fan, pump), and heat and mass transfer components (coils, humidifiers).*
- *Start node: Building node at the location of the vertical shaft on floor.*
- *System node: Building node at the location of the secondary system.*
- *Plenum: Collection of building nodes through which ducts or pipes can pass.*



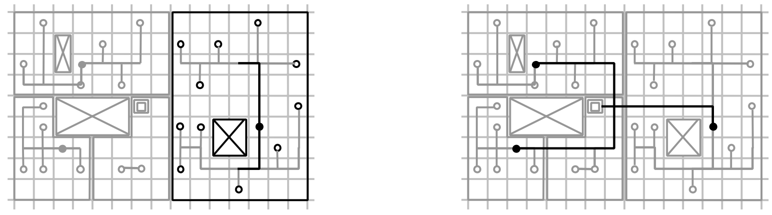
Input for distribution layout generation

Step 1: Find min and max coordinates



Step 2: Establish Clusters

Step 3: Connecting terminals to the cluster branch



Step 4: Generate zone branch

Step 5: Connecting zones points to start node

Figure 5: Distribution network design sequence

Heuristic Rules: These are based on the analysis of the common practice of network design and the rules that are used by HVAC designers. It is assumed that all the spaces in a zone are contiguous.

1. The network should be as symmetric as possible.
2. There would be a maximum of five levels of branches:
   - Terminal branch: Connects the terminals to the cluster branch
   - Cluster Branch: Centrally placed branch in the cluster to which terminals are connected.
   - Zone branch: Connects all the cluster branches in a zone.
   - Main branch: Connects all the zone branches to the start node on each floor.
   - Vertical branch: Connects the main branches on each floor to the system node.
3. Branches in one zone would not intersect with branches of another zone.
4. Main branch will avoid intersecting any zone branch.

Algorithm: The nodal representation of the building is utilized in the automatic generation of the network. Figure 5 graphically shows the steps used in the network design algorithm. The algorithm, which is recursive in nature, is outlined below:

1: Find the maximum and minimum *x*,*y* coordinates of the terminals in a zone.

2: Establish a cluster size (about 9-10 m). If any of the distances are smaller than or equal to the cluster size, the zone has one cluster, else divide the zone into clusters.

3: Generate branch along the longer axis of the cluster as centrally as possible. Connect the terminals to this branch. The center point of the cluster branch is the cluster point.

4: Follow step 3 for all the clusters in the zone. Repeat it on the cluster points. This is the zone branch. The center point for the zone branch is the zone-point.

5: Connect each zone-point to the start node, starting with the farthest zone-point.

6: Similarly, connect the system node to the start nodes.

At any step, only two nodes are connected to each other. This is done by using the shortest-path algorithm (Horowitz et al. 1993). The distance used between any two nodes to calculate the shortest path considers the actual length of the path, any turns in the path, and whether it crosses any terminal/branch. The use of this algorithm ensures that obstructions and openings are taken into consideration when deciding the path. The algorithm can be applied for multiple systems serving a zone or the whole building.

Once the layout nodes are obtained, the design agent parses the node information to generate the list of actual distribution network components (e.g. duct, pipe, fitting, valve, damper, Variable Air Volume box) and establishes the connections between them and the terminal and generation components. Now the DOM is complete and the performance analysis of the building can be conducted.

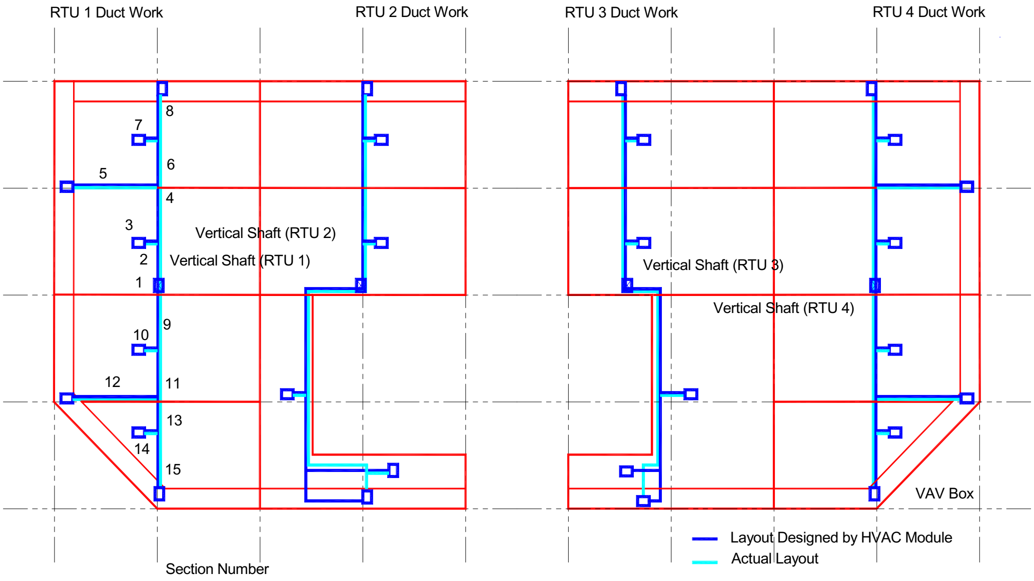


Figure 6: Automatic Duct Layout Generation: Open Plan Office Area, Building A

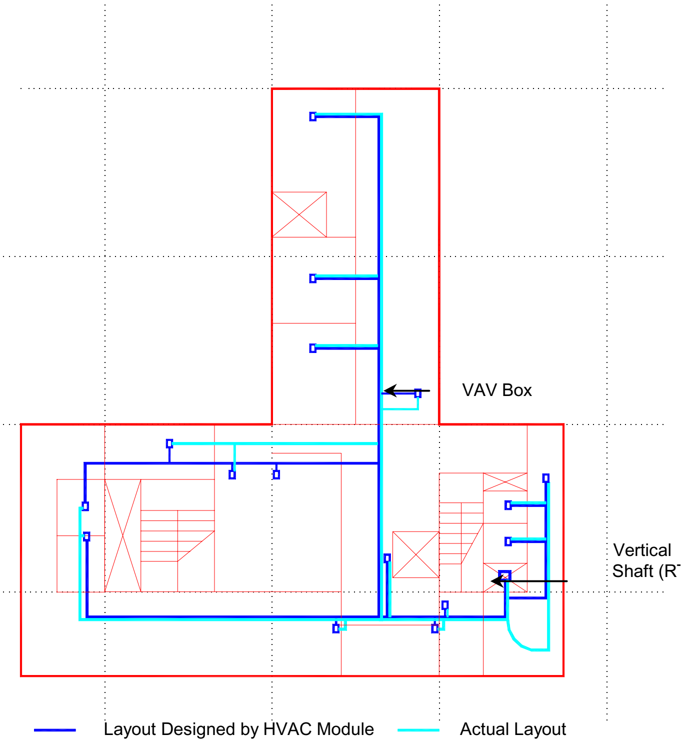


Figure 7: Automatic Duct Layout Generation: Core Section, Building

ILLUSTRATIVE EXAMPLES

Duct layout generation and sizing

To demonstrate the feasibility of the proposed two-staged mapping and generative design agent approach, we conclude the paper with illustrative examples of detailed performance analysis of complex buildings and their systems, performed in early stages of design. An actual office building (Building A), located in Pittsburgh has been chosen for the automatic layout generation case study. Building A has two floors and is served by five Roof-Top Units (RTU). To demonstrate the layout generation, only one floor has been modeled. Four of the RTU's serve the open plan office space. The distribution is floor-based and open plenum with ducts running from the vertical shaft to the Variable Air Volume (VAV) boxes. The fifth RTU serves the core area and is ceiling-based and has ducted plenum.

This study involved the generation of duct layout given the location of VAV boxes. Here the location of the vertical shaft is the start node and the location of the VAV boxes the terminal nodes. As Figure 6 and 7 show, there is a good match between the actual and the generated network for the core and the open plan office area.

Table 1: Comparison of duct sizes for RTU1

Section Number	Length (m)	Flow (l/s)	Actual Duct Diameter (m)	Generated Duct Diameter (m)	Percentage Difference
1	1	4969	0.84	0.84	-0.6%
2	5	2652	0.66	0.75	-13.0%
3	2	812	0.43	0.41	2.8%
4	5	1840	0.58	0.62	-6.5%
5	9	566	0.41	0.34	16.8%
6	4	1274	0.51	0.52	-0.5%
7	2	708	0.41	0.38	5.1%
8	5	566	0.38	0.33	13.7%
9	5	2317	0.64	0.70	-10.3%
10	2	812	0.43	0.41	2.7%
11	5	1505	0.56	0.54	3.2%
12	9	481	0.36	0.31	14.9%
13	3	1024	0.48	0.44	9.0%
14	2	543	0.38	0.31	18.8%
15	6	481	0.36	0.30	15.9%

For RTU 1, the sizes of the ducts designed by the HVAC design agent are compared with the actual sizes in Table 1. The sizes designed by the generative agent are within 20% of the actual sizes. This may be seen as an acceptable range, given that the difference in sizes designed by various methods can be as high as 50% (Brahme 1999).

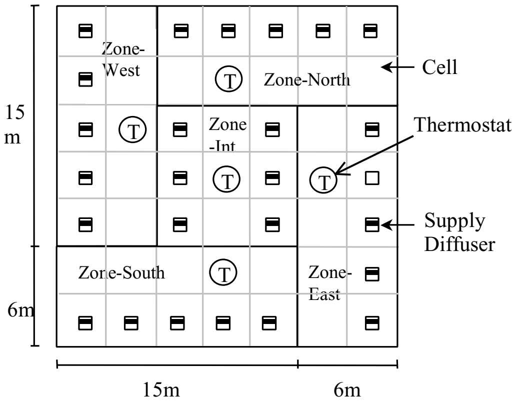


Figure 8: Typical Office Building Plan

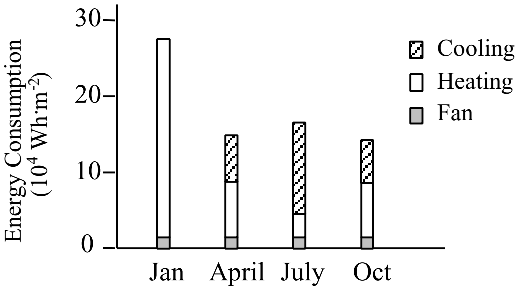
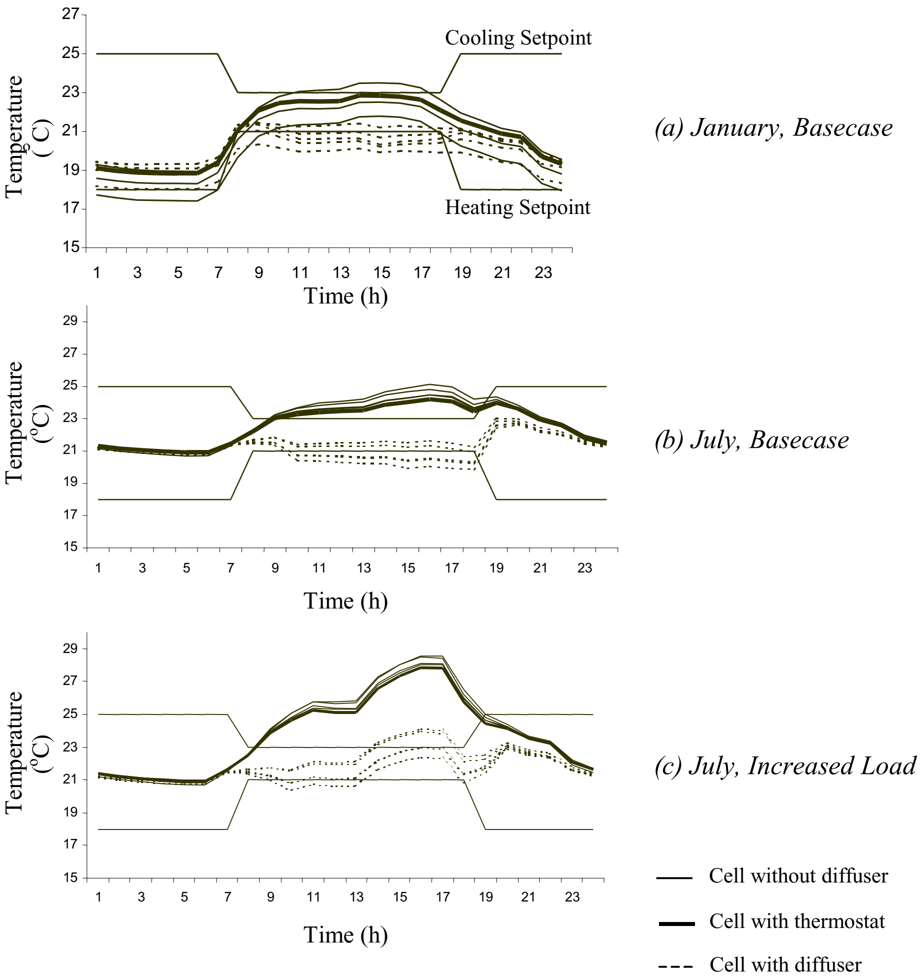


Figure 9: Energy consumption, Basecase



(a) January, Basecase

(b) July, Basecase

(c) July, Increased Load

Figure 10: Temperature profile of cells in Zone-West

Energy Analysis of an air-based system

For the annual energy consumption analysis, a typical office building (located in Pittsburgh) was modeled (Figure 8). The system is assumed to be a Constant Air Volume (CAV) system with reheat coils at the zones. Simulation is performed for four months - January, April, July, and October. The building is 21 m by 21 m, consisting of five zones - one interior zone (9 m by 9 m) and four perimeter zones (6 m by 15 m each). The diffuser and thermostat locations are given as input. The HVAC design agent generates the duct layout for this diffuser configuration, automatically sizes the layout and the system, and computes the system energy consumption.

Figure 9 shows the heating, cooling and the fan energy consumption for the four months. Figure 10 shows the simulated temperature profiles for the cells in Zone-West.

Figure 10a and 10b show the temperature profiles for the cells in Zone-West for a day in the months of January and July respectively. It is interesting to note that the simulation predicts the expected temperature difference between the cells with diffuser and those without diffuser during the occupied hours.

We also studied the change in the usage of a space by changing the loads in one of the zones and following its influence on the room temperatures, while keeping the system parameters same as in the base case. The internal loads (people, light, equipment) in the west zone are increased from 35 W/m^2 to 75 W/m^2. Figure 10c shows the temperature profile for the west zone. Overall the temperatures in all the cells have increased, compared to the base case (Figure 10b). The cells with the diffusers are now within the setpoints but the temperatures in the cells without the diffusers are rather high.

CONCLUSIONS

Through the development of a differential building representation and use of a generative agent for simulating the HVAC sub-system, this paper demonstrates that it is feasible to:

- integrate the analysis of technical sub-systems in the early stages of design, while still using detailed modeling techniques;

- increase the effectiveness of the simulation tool by reducing the input information required from the user. This also makes the analysis of the buildings' technical sub-systems more accessible to a general user, thus extending its relevance beyond the realm of domain experts.

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