Performance-based computational design via differential modeling and two-staged mapping

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Key words: building performance simulation, homology-based mapping, intelligent design agents

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 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 technical sub-systems are not yet available. In this paper, we demonstrate how this problem can be partially solved by combining two levels of automation. The first level consists of differential building representation involving a number of domain (application-specific) object models that are derived from a shared object model automatically. The second level uses generative agents that create reference designs for the technical sub-systems of the building. To demonstrate the feasibility of the proposed approach, we use the building energy systems domain (heating, cooling, ventilation, and air-conditioning) as a case in point.

1. INTRODUCTION

Certain levels of building performance analysis may be more relevant to the types of questions that primary building designers (particularly architects) must explore. Such questions address, for example, the effects of building enclosure and glazing, massing, orientation, natural ventilation. Performance analysis of detailed building technical sub-systems is usually associated with the activities of the domain specialists (e.g., lighting, energy, and acoustic experts). However, buildings' overall performance is considerably affected by the design of the technical sub-systems. This circumstance poses a challenge to the developers of building performance analysis tools: How can we provide performance feed-back to the designer as early as possible in the design process, while considering the effects of 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 information on building's sub-systems is either not available or is schematic at best. Such a method could deepen and extend the type and range of building performance queries that a general user (for instance, the primary building designer) could pursue early on in the design process.

Our approach toward a partial solution to this problem involves differential modelling and two levels of mapping:

1. Differential building representation - A general building representation (SOM, or shared object model) incorporates most of the information needed for the configurational definition of the building early in the design process (Mahdavi 1999). The detailed information on building's technical systems is captured in various disciplinary representations (DOMs, or domain object models). The first automated mapping operation (homology- based mapping) allows for the derivation of a basic DOM from SOM (Mahdavi and Wong 1998, Mahdavi et al. 1997). However, to perform computational building performance analysis, this basic DOM must be augmented with further detailed technical information. Such information is typically provided by the user. To do this without user intervention, a second automated mapping operation is needed.
2. Generative sub-system design agents - To perform the second automated mapping operation (from the initial DOM to a complete DOM), we adapt a technical sub-system design agent approach. As a case in point, we consider design agents for building's energy systems. We describe one such agent that automatically generates a layout for the building's energy delivery network (e.g., duct/pipe system) with minimal inputs from the user (high-level definition of the energy system type). Generally, the network design is undertaken during the later stages of design when most of the relevant decisions (e.g., location of the mechanical room, number of thermal systems, plenum size) have already been finalized. We demonstrate how a design agent can generate, in this case, a network lay-out using a combination of heuristics and shortest-path algorithm.

2. DIFFERENTIAL BUILDING REPRESENTATION

Building performance analysis can be performed at various levels of depth and resolution. From a software engineering point of view, this represents a number of problems. 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). Our experience in this area has led us to a differential building representation approach. This approach distinguishes between a general building model and various building models for the different technical disciplines (Mahdavi 1999).

The general building model (SOM - shared object model) incorporates most of the information needed for the configurational definition of the building early in the design process (cp. Figure 1). It is the result of a bottom-up approach that began with the study of the informational requirements of a discrete set of building performance analysis applications. Two important criteria informed its development: *a)* the SOM should reflect a building representation that is transparent to building designers, and *b)* the domain object models for each of the applications should be derivable from the SOM without user intervention (Mahdavi et al. 1997).

The core technology to support this SOM-to-DOM derivation is a kind of homology-based mapping mechanism. Using it, it is possible, in principle, to make evolving building designs subject to comprehensive parametric studies in multiple domains without having to input the building model separately for each application (Mahdavi et al. 1998). Thus, building performance feedback may be provided to the user in an effective and timely fashion.

The detailed information on the building's technical sub-systems is captured in various disciplinary representations (DOMs - domain object models). Within the framework of the SEMPER project (Mahdavi 1999) such domain objects models have been developed for applications in energy and airflow analysis, lighting, acoustics, and environmental impact analysis.

Note that, the primary DOM that is derived from the SOM does not have, in most cases, the entire set of data needed for analysis. While basic passive energy analysis and daylight simulation may be performed based on respective primary DOMs, applications that involve extensive technical equipment and hardware (e.g. HVAC, electrical lighting) require additional information.

Figure 2 shows, as an example, the DOM of the HVAC sub-system. The highlighted boxes show the information that is automatically mapped from SOM. The HVAC simulation module utilizes a representation consisting of spatial units (cells) with nodes that define finite control volumes (Figure 3).

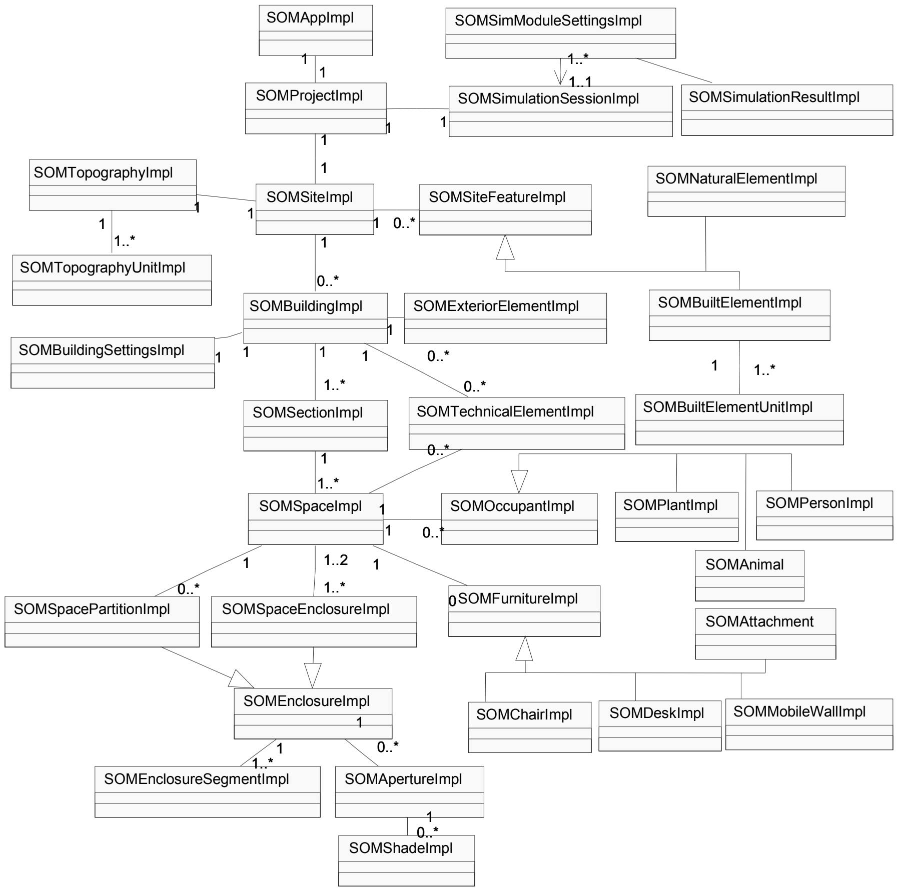


Figure 1. Shared Object Model (primary physical elements, UML notation)

A 3-dimensional grid for discretizing the spaces into cells is adopted, which serves as a framework for designing and modelling the HVAC distribution network and terminal unit design. The nodal representation of the building is configurationally homologous to the space-based building representation in the SOM and is automatically derivable from it. However, for a full HVAC analysis, two further conditions must be met:

i) The SOM must also incorporate some basic information for the various technical sub-systems to facilitate the second automated operation. In case of the HVAC sub-system, this consists of minimal information - the system type and location (to decide whether it is a pipe network or a duct network and its starting point) and the location of the distribution network (to decide if it is a ceiling based or a floor based system). Such information is readily available even during the early stages of design.

ii) Generative design agents must be developed that can carry out the second automated operation. They must be able to generate autonomously reference (default) designs of technical systems such as the layout of the energy distribution network. We discuss this in the next section.

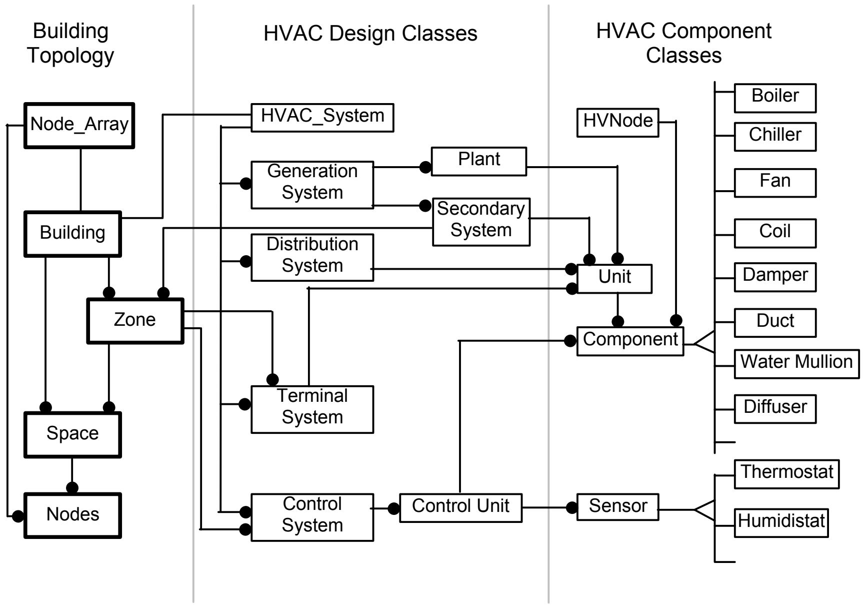


Figure 2. Domain Object Model

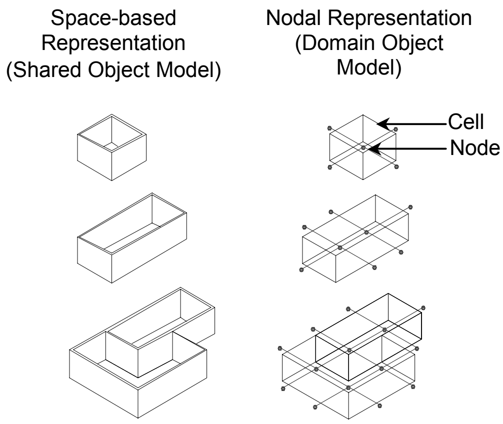


Figure 3. Homology-based mapping

3. TECHNICAL SUB-SYSTEM DESIGN

3.1 Overview

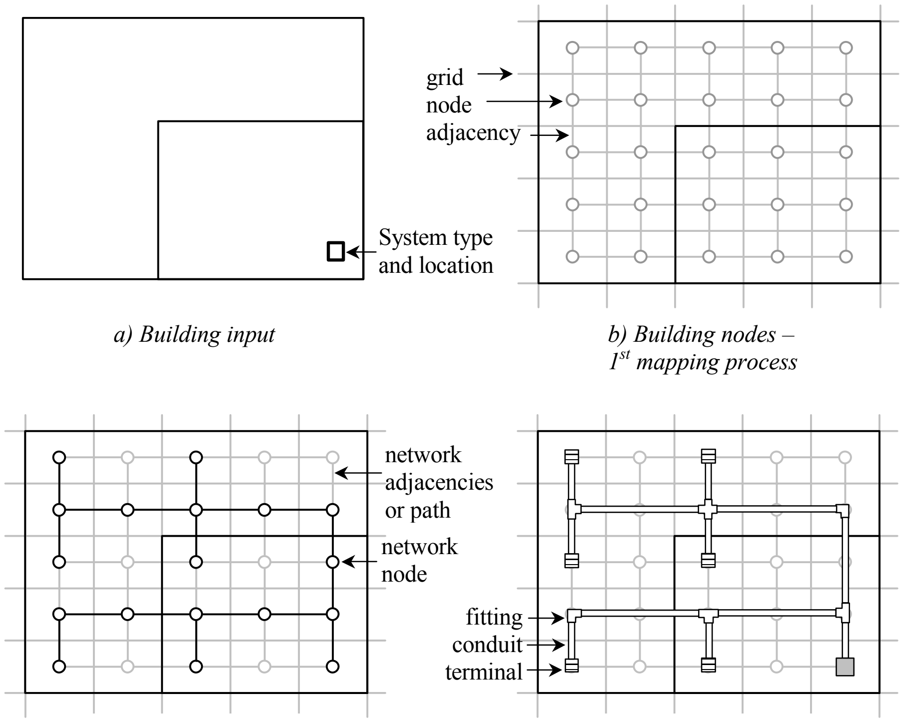
The first homology-based automated mapping operation allows for the derivation of a basic DOM from SOM. However, to perform computational building performance analysis, a complete DOM is needed. In case of the HVAC domain, such a complete DOM must entail a full description of the HVAC design classes and the component classes in order to allow for a performance analysis. To achieve this without user intervention, a second automated operation is needed - from the initial DOM to a complete DOM. Toward this end, we adapt a technical sub-system design agent approach.

Let us consider the case of HVAC domain again. Once the building design classes are obtained by the first mapping process (Figure 4, b), the remaining information needed to complete the HVAC DOM is generated automatically by using a generative design agent. Briefly, the design agent uses: *i)* the system type information to generate the components for the generation system; *ii)* certain heuristics to design the terminal system; *iii)* a combination of heuristics and shortest-path algorithm to design the distribution system components (Figure 4, c and d).

Once the system design is complete, all the 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 calculated automatically at each time step, for the specified time frame.

3.2 Distribution System Design

Typically, the energy distribution system of a building conveys a heating or cooling medium from the generator location to the portion of a building that requires conditioning. It is 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 affect on energy consumption, if the network has to be designed and manually entered into the tool for each configuration. Thus, it seems that an automatically designed network could be useful in evaluating such alternatives, especially at the initial design phase.



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

In our implementation, the design agent used for the automated generation of reference (standard or default) distribution networks uses a combination of heuristics and shortest-path algorithm. The inputs for the design agent are 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. We can now proceed with the description of the second automated process and the distribution system design agent's functionality. This we do by establishing a terminology, summarizing the underlying heuristic rules, and describing the relevant algorithm.

Terminology: For a better understanding of the functionality of distribution system design agent, the following terms should be kept in mind.

- *Zone:* A group of 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.
- *Start node:* The building node at the interface of the vertical distribution shaft with the floor.
- *Secondary system:* The secondary system equipment consists of prime movers (fan, pump), and heat and mass transfer components (coils, humidifiers, dehumidifiers). Secondary systems serve one or more sections of the building.
- *System node:* The building node at the location of the secondary system.
- *Plenum:* The set of building nodes at each floor (or level) through which ducts or pipes can pass.

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 shall 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 cannot intersect with branches of another zone.
4. Main branch cannot intersect any zone branch.

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

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

Step 2: Establish a cluster size (usually 9 to 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.

Step 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.

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

Step 5: Connect each zone point to the start node, starting with the furthest zone point.

Step 6: The system node is similarly connected to the start nodes (this is not shown in the figure).

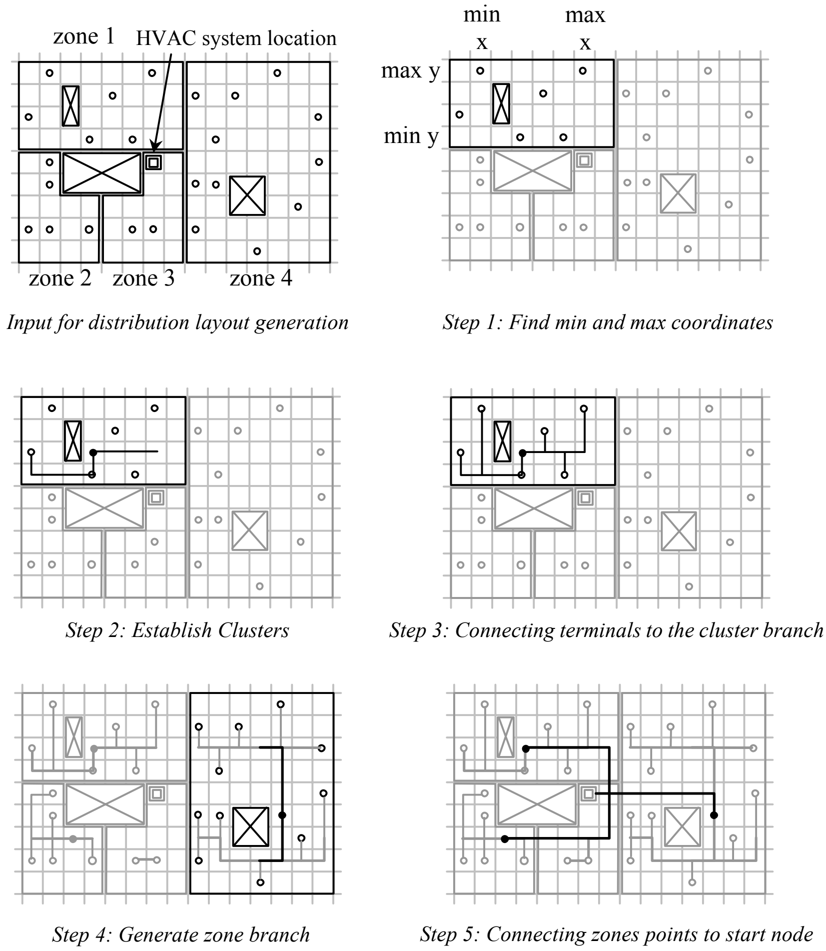


Figure 5. Distribution network design sequence

At any step, only two nodes are connected to each other 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 or branch. The use of this algorithm, in conjunction with the node discretization of the building, ensures that obstructions and openings (voids) are taken into consideration while deciding the distribution network's configuration. 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 a list of actual distribution network and establishes the connections between them and the terminal and generation components. Examples for distribution network components are duct, pipe, fitting, valve, damper, VAV (variable air volume) box.

At this stage the DOM may be considered complete and the thermal performance analysis of the building can be conducted.

4. ILLUSTRATIVE EXAMPLES

4.1 Objective

To demonstrate the functionality of the system, we offer some illustrative examples of detailed performance analysis of complex buildings and their systems, conducted in early stages of design.

4.2 Duct layout generation and sizing

An actual office building (Building A), located in Pittsburgh was selected for the automatic layout generation case study. By choosing this building for case study, it is possible to compare the automatically generated layout with the layout independently designed by the project's mechanical engineer. Building A has two floors and is served by five Roof-Top Units (RTU). To demonstration the layout generation, only one floor has been simulated. Four of the RTU’s serve the open plan office space. The distribution is floor-based and open-plenum with ducts extending from the vertical shaft to the VAV boxes. The fifth RTU serves the core area, is ceiling-based and with a ducted plenum.

This study involved the generation of duct layout given the location of VAV boxes. Here the location of the vertical shaft constitutes the start node and the location of the VAV boxes the terminal nodes. As Figure 6 and Figure 7 demonstrate, there is a good match between the actual network for the core and the open plan office area (as designed by the mechanical engineer) and the computationally generated network.

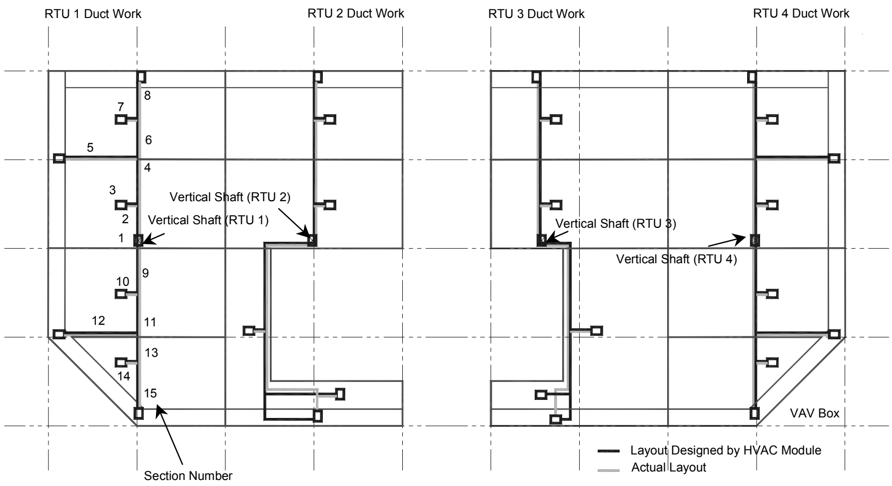


Figure 6. Automatic duct layout generation: open plan office area, Building A

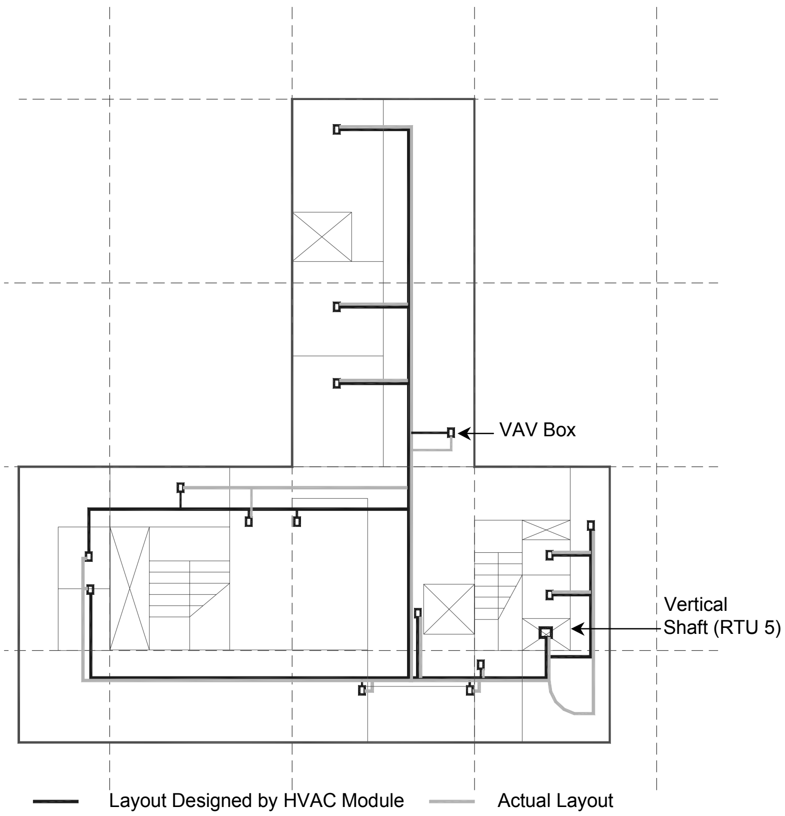


Figure 7. Automatic duct layout generation: core section, Building A

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 agent are within ±20% of the actual sizes. This is generally considered to be acceptable range, as various sizing methods result, in practice, in variations in the ±50% range (Brahme 1999).

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	-0.7
2	5	2652	0.66	0.75	-13.1
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	16.9
6	4	1274	0.51	0.52	-0.6
7	2	708	0.41	0.38	5.2
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	18.9
15	6	481	0.36	0.30	16.0

4.3 Energy analysis of a air-based system

To demonstrate the systems capabilities for the computational analysis of the annual energy consumption and thermal indoor conditions, a typical office building located in Pittsburgh was selected (see Figure 8). The building consisted of five zones - one interior zone and four perimeter zones. The mechanical system was assumed to be of Constant Air Volume (CAV) type with reheat coils at the zones. The diffuser and thermostat locations were given as input information. Using its embedded design agent, the HVAC application generated the duct layout for this diffuser configuration and automatically sized it. Figure 9 shows the simulated temperature profiles for the cells in Zone-West for the month of January. Figure 10 shows the heating, cooling and the fan energy consumption for four months – January, April, July, and October.

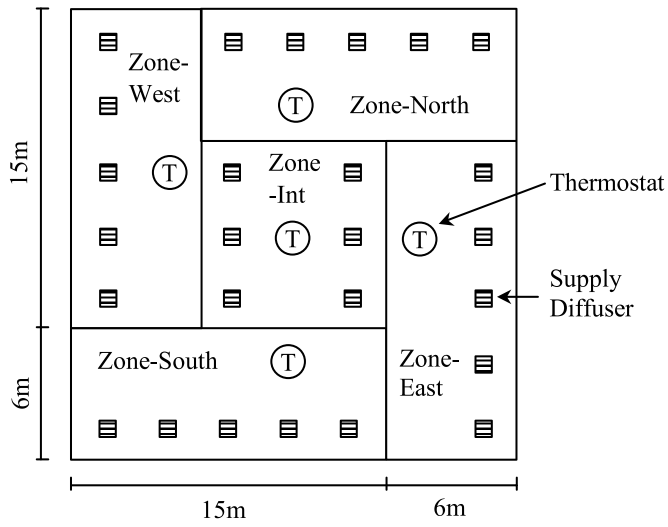


Figure 8. Typical office building plan

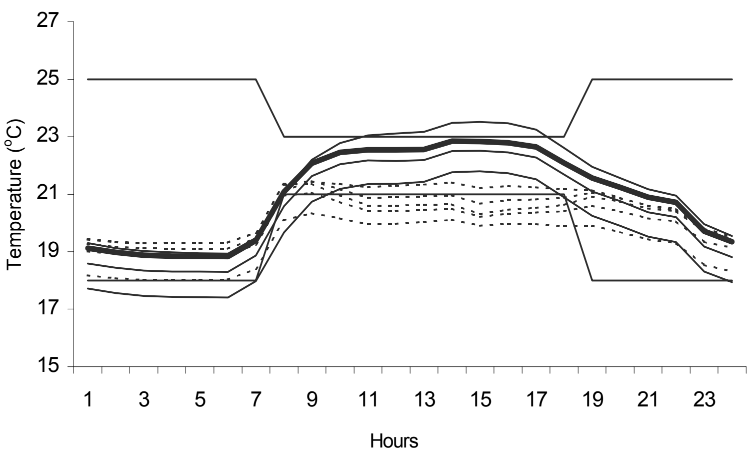


Figure 9. Temperature profile for Zone-West (January)

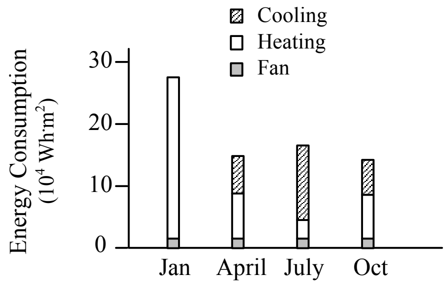


Figure 10. Energy consumption

5. CONCLUDING REMARK

We presented a computational approach to support an extended set of early-design performance queries based on a differential building representation and the use of generative agents for the design and modelling of buildings' technical systems. Using the domain of building energy systems as a case in point, we demonstrated that complex technical systems may be subjected to detailed performance analysis even in the early stages of design. We believe that by adapting this approach, detailed computational building performance assessment tools may become more accessible to a general user, extending its relevance beyond the realm of domain experts.

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