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SELF-AWARE BUILDINGS: A SIMULATION-BASED APPROACH

Ardeshir Mahdavi[1,2], Rohini Brahme[1], Smita 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

This paper describes the "Self-aware Buildings" (SAB) project. This is an effort to advance the state of knowledge and technology in the area of environmentally conscious and user-sensitive integrated building control systems. An evolving test bed (SAB cell), its systems, and its information infrastructure are described. Spicifically, simulation-based approaches toward the integrated control of complex building and indoor environmental systems are explored.

1. INTRODUCTION

Currently, the many sub-systems involved in the operation of a modern building are not effectively integrated. Even though a device (e.g. a heating delivery device) may be of high technical quality, it is typically neither well integrated with other devices (e.g. a lighting device) nor with the building hardware (the architectural object). The resulting overall performance is thus sub-optimal. Moreover, there is a lack of robust methods to guarantee that the working of the system satisfies economical criteria, ecological considerations, and user needs. To address these problems, innovations in building design, building systems, and building delivery process are required. The "Self-aware Buildings" (SAB) project represents a step in this direction. Specifically, the SAB project aims at the

a) provision of a modular, distributed, flexible, and scalable infrastructure to collect information (on micro-climate, indoor environmental conditions, status of technical building support systems such as heating, cooling, lighting, etc.) and actuate environmental control and modification devices and systems;

b) design of an advanced building information system to generate and maintain models of buildings and to use those for building systems control purposes. Such models address buildings' actual (current) operational status, buildings' past behavior/status (building memory system), and buildings' future operation (generation and evaluation of building control schemes and sequences using a multitude of advanced control algorithms;

c) design and evaluation of intuitive, flexible, and hierarchically organized interfaces between building users and building operation systems to ensure *i)* locally optimal environmental conditions and *ii)* globally sustainable building operation.

In the following, we describe the four constitutive SAB elements (cp. table 1). These are: physical setting, systems, information infrastructure, and information processing tools/methods.

2. PHYSICAL SETTING AND SYSTEMS

For the purposes of the SAB project, we distinguish four levels of hierarchy in the physical setting: space, section, building, and site. The space (SAB cell) selected for developing and testing the first version of SAB prototype is one half of a bay in the intelligent workplace (IW) as shown in Figures 1. IW is a recently established laboratory on top of an existing building (MMCH) in the Carnegie Mellon University campus (Pittsburgh, USA) for demonstration and hands-on study of advanced building systems and technologies (Mahdavi et al. 1999a). The sections are the north and south parts of the IW. In the SAB prototype, we refer to IW as the building and MMCH as the site. The systems available in the SAB project's space, section, building, and site are described in Table 2.

3. INFORMATION PROCESSING INFRASTRUCTURE

The information infrastructure currently realized in the SAB project consists of the instrumentation of the SAB-cell and a system architecture to facilitate the connectivity between different hardware components, as well as the connectivity with the user. Figure 2 illustrates the relationship between the various infrastructure components.

TABLE 1. The four elements of the SAB research project

Elements of SAB	Definition	Currently realized in SAB project
Physical setting	The architectural space	the SAB cell
Systems	heating, cooling, ventilating, lighting and control systems	Personal Environmental Module, electrical lighting, moveable louvers
Information processing infrastructure	sensors, computers	light and temperature sensors, device actuators, data field-points, SAB server
Information processing tools and methods	standard and proprietary software	data collection, data storage and analysis, visualization, control programs

TABLE 2. SAB Systems

	System	Description
Space (SAB cell)	User-based indoor environmental control system	HVAC terminal unit located at the users worksta tion. The user can control the amount of air flow and its direction and temperature.
	Water Mullion	Integrated with the enclosure: Depending on the need for energy extraction/addition, hot or cold water flows through water mullion.
	Electrical lighting	Luminaires with dimmable ballasts and T-5 fluorescent lamps.
	Operable windows and blinds	High insulating, high visible transmission double-glazing with user-controlled interior blinds
Section (north and south parts of IW)	Air-handler	Serves the south section of the building. It provides dehumidified and cold air
Building (IW)	Movable louvers	The dynamic facade consists of motorized light redirection louvers.
	Water Mullion	Control components for water mullion system: pump and the valve to attain required supply water temperature.
Site (MMCH)	Heat-exchanger	Converts the campus steam to hot water for water mullions.
	Campus chilled water	Used for cooling by both the water mullion system and the air-handler.

IW's weather station has six sensors to measure temperature, relative humidity, pressure, solar radiation, and wind speed/direction. The daylight station measures the illuminance and irradiance values on four vertical surfaces (north, east, south, west) and the horizontal surface. It also measures the diffuse solar irradiance. Inside SAB-cell, we measure the light levels at four locations, the surface temperature at eight points on the facade, and the CO_2 concentration.

4. INFORMATION PROCESSING TOOLS AND METHODS

4. 1 Data Collection and storage

A commercially available software is used for the purposes of collection of indoor and outdoor sensor values. This data can be used for various purposes such as understanding IW's energy consumption, diagnosing operational problems, and providing feedback to occupants. The database for the project is aimed to store data collected from a variety of sensors, to supply analytical feedback on daily operational problems and environmental change, and in the future, to provide environmental information to SEMPER software (Mahdavi 1999) for simulation and validation purposes. A commercially available relational database is used because it supports *a)* user-defined data types, *b)* Java and Enterprise JavaBeans, *c)* development of CORBA applications, *d)* multimedia data, *e)* data protection, and *f)* on-line transaction processing and data warehouse applications.

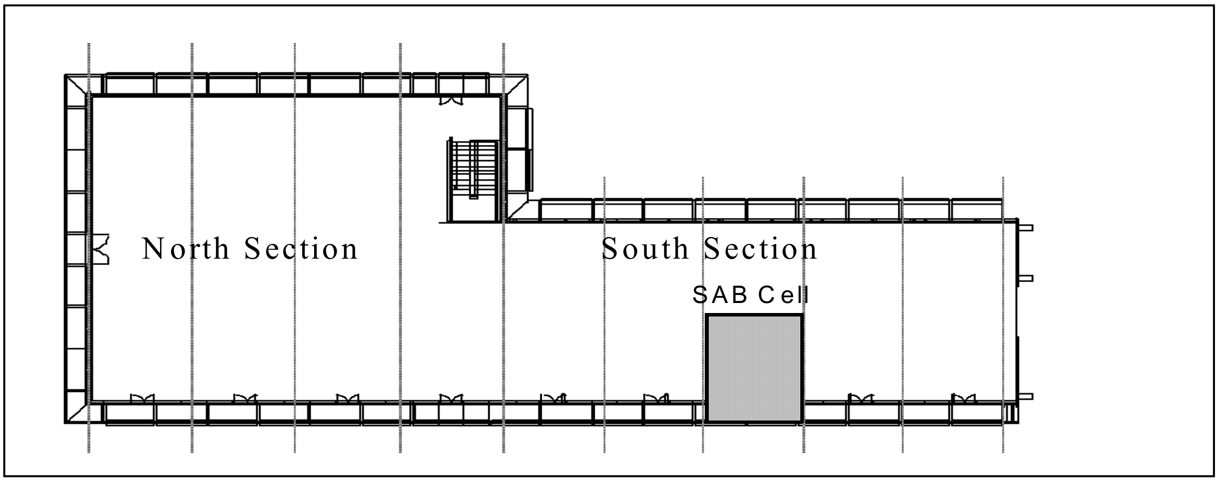

Figure 1. SAB-cell in the IW

4.2 Data Mining

Data mining involves data preparation, interpretation, and results deployment. A set of scripts have been developed for the data preparation (Buchheit et al.2000). A rough sets tool was used to model the IW data. This tool uses a genetic algorithm to choose which attributes to include in each rule. In one case study, three models were built. The first model describes how outside air temperature affects the hot water supply temperature at a heat exchanger. The second model describes how outside air temperature, solar radiation, and wind speed affect hot water energy consumption. The third model describes how outside air temperature, relative humidity, and wind speed affect chilled water energy consumption.

4.3 SAB User Interaction Environment

There are multiple users in every building that need access to environmental controls, including the actual occupant of each workspace, visitors, maintenance staff, and the facility managers. In this context, each user needs a simple, intuitive, and consistent interface. We have implemented a prototype for the occupant interaction environment for the SAB cell. The interface is a graphical, hierarchical, window system that allows the occupant to control lighting, heating, cooling, and ventilation within the SAB cell. In general, the information in the interface can be categorized as navigation, status or control information. The interface prototype allows the user to access the current values of the visual, thermal,

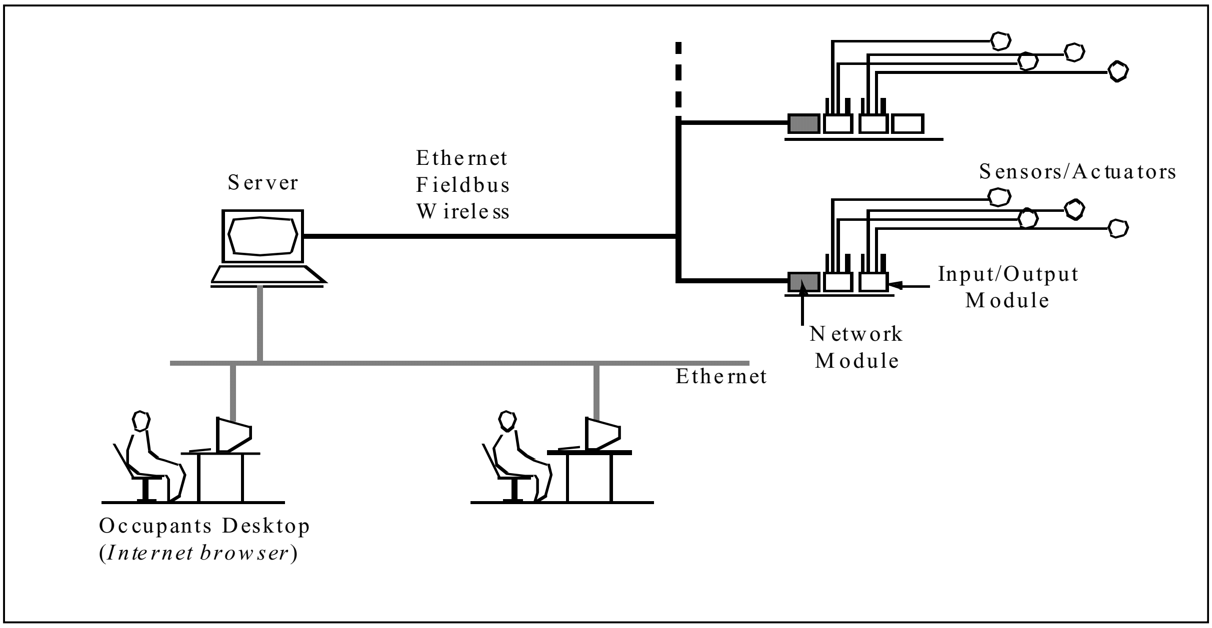

Figure 2. Infrastructure scheme for a self-aware building prototype

and air quality parameters within the applicable control zone, the current weather data, and energy use on the log-in window. From here, the user can venture into deeper levels of information via specialized windows for lighting, energy, and other systems.

4.4 Control approaches and algorithms

To address the shortcomings of the existing approaches to building systems control, we have focused in the SAB project on developing new methods for the control of complex building systems. Specifically, we have explored nested rule-based and model-based control approaches for the operation of the environmental systems. These approaches are described in more detail in sections 5 and 6 respectively.

5. A RULE-BASED CONTROL APPROACH

5. 1 Overview

The fundamental principle in rule-based control is to use "if this, do that" rules that dictate what actions the control system should perform under certain circumstances. Exactly what these rules should be is decided upon in the design phase of the control system. The collection of all such rules should completely describe the actions dictated by the controllers. A rule base is naturally modular, each rule containing one piece of information or knowledge about how the system should act in a given situation. Rule-based control is inherently flexible. Rules can be easily added, deleted, or changed. The setpoint or "if-condition" described in the rule can be easily modified by the user (occupant or facility manager), or the resulting action can be changed. Each of these features could improve the quality of the building control system over traditional methods. In preparation for the application of rule-based control, we decomposed the IW environmental systems into an ordered, nested, hierarchy. The complex system is separated into smaller, less complex systems, and this process continues until a sub-system is reached for which a solution can be formulated. Each control objective can be described by a series of rules which are distributed among the controllers. Rules which appear lower on the hierarchy are concerned with specific tasks of a device (such as a luminaire or louver). Those on a higher level have supervisory functions between multiple devices (such as the coordination between an occupancy sensor, a louver, and a luminaire).

5.2 The Example of the Louver System

In order to derive rules for controlling the indoor illuminance conditions in the test cell, using the exterior louver system, we explored the relationship between the angle of the exterior louver and daylight factor. We obtained indoor and outdoor illuminance measurements for 22 different louver angles for every hour over a period of two months. The data set includes measurements from 12 indoor illuminance sensors, an outdoor global illuminance sensor, and outdoor illuminance sensor measuring illuminance on a vertical surface facing west.

Figure 3 shows the relationship between the average daylight factor (defined in this case as the ratio of average indoor illuminance over the 12 sensors divided by the external vertical illuminance incident on the building's west facade) and the louver angle. The relationship can be expressed by the following formula:

$$DF = 0.0004\,\theta^2 - 0.0135\,\theta + 6.2927 \qquad [1]$$

Here, θ is louver angle (in degrees) and *DF* is daylight factor (in %).

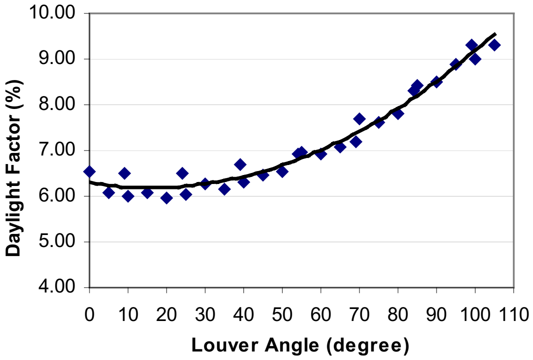

Figure 3: Effect of louver angle on daylight factor in the test-cell

Given this relationship, rules may be formulated that map a desired change in the indoor illuminance level back to the appropriate louver position.

6. A MODEL-BASED CONTROL APPROACH

6.1 Motivation and Rationale

Modern buildings allow, in theory, for multiple ways to achieve desired environmental conditions. For example, to provide a certain level of illuminance in offices, daylight, electrical light, or a combination thereof can be used. The choice of the system(s) and the associated control strategies represent - from the theoretical point of view - a non-trivial problem. This has implications for the objective function of the control strategy. The objective function of a control strategy typically address one or more of the following criteria: *a)* desirable environmental conditions for the inhabitants, *b)* energy-effectiveness of the operation, and *c)* minimization of environmental impact. The reason for this nontriviality is that there is no simple function that correlates the objective function with the building controls state.

Model-based control can potentially provide a remedy for this problem (Mahdavi 2000, Mahdavi 1997, Mahdavi et al. 1999b). Instead of a direct mapping attempt from the desirable value of an objective function to a control systems state, the model-based control adopts an "if-then" query approach. To achieve this, first the control state must be parametrized. For example, for lighting controls in IW, discrete louver positions for the external shading devices may be defined. Likewise, the light output of the luminaires in the space may be parametrized in terms of discrete dimming states. Given the description of the space and the discrete control system values, multiple simulation are performed for various combinations of such values. The simulation results, that is the values of the objective function(s), are then ordered in a table, which is used to select the most desirable control scenario

6.2 Constructing the control state matrix for the SAB cell

Table 3 describes the control state matrix for SAB’s various systems. The performance indicator column highlights the variables that the model-based control algorithm is intended to optimize. Each system is responsible for controlling one or more variables in a space. For example, the water mullion at the space level is responsible for controlling the energy extraction/addition. This is achieved by changing the water flow in the mullion. The actuator in this case is the valve, whose position affects the amount of flow in the water mullion.

6.3 A case of model-based lighting systems control

A lighting simulation tool can be applied to predict indoor light levels as the necessary input information for a model-based control of buildings' lighting systems (Mahdavi et. al. 1999b). IW's facade system includes a set of three parallel external moveable louvers, which can be used for shading. These motorized louvers can be rotated anti-clockwise from a vertical position up to an angle of 105^{o}. An array of 12 illuminance sensors is located in the central axis of this space at a height of about 0.8 m above the floor. Outdoor light conditions are monitored using 11 illuminance and irradiance sensors that are installed on the daylight monitoring station. LUMINA (Pal and Mahdavi 1999), the lighting simulation application in SEMPER (Mahdavi 1999) is used for the prediction of light levels in the test space.

As an initial feasibility test of the proposed model-based control approach, we considered the problem of automatically determining the "optimal" louver position among four discrete louver positions, namely 0^{o} (vertical), 30^{o}, 60^{o}, and 90^{o} (horizontal), towards fulfillment of daylight- related objectives. Consider two illustrative objective functions. The first function aims at minimizing the deviation of the average (daylight-based) illuminance level E_m in the test space from a user-defined target illuminance level E_t. The second objective function aims at

TABLE 3. Control states for selected systems in the SAB cell

Physical Setting	Performance Indicator	System	Variable	Actuator	Control State (%)
Space	Temperature Light Level	PEM	Temperature	Damper	10, 40, 70, 100
			Flow	Fan	0, 50, 100
		Water Mullion	Flow	Valve	0, 33, 67, 100
		Electrical Light	Light level	Ballast	0, 10, 20, .., 90, 100
		Window	Opening	Manual	Open/Close
Section	Energy Consumption	AHU	Outdoor air flow	Damper	30, 50, 70, 100
			Supply temperature	Cooling Coil valve	0, 33, 67, 100
			Supply flow	Fan	30, 50, 70, 100
Building	Energy Consumption	Water Mullion	Temperature	Valve	0, 33, 67, 100
		Louvers	Tilt	Motor	0, 45, 90, 135 (angle)
Site	Energy Consumption	Heat exchanger	Flow	Valve	0, 33, 67, 100
		Chilled water	Flow	Valve	0, 33, 67, 100

maximizing the uniformity (Pal and Mahdavi 1999) of the illuminance distribution in the test space. The model-based louver control scenario in this case proceeds as follows. At time t_i, the simulation tool predicts the expected illuminance levels in the space for the time interval t_{i+1} for four candidate louver positions (test space geometry and photometric properties, as well as the outdoor measurements at time t_i are used as model input). Based on the predefined objective functions, the simulation tool identifies the louver position which is likely to maximize the light distribution uniformity or to minimize the deviation of average illuminance from the target value. An empirical test of this approach showed it to be feasible (Mahdavi et. al. 1999b).

6.4 Challenges and Solutions

The central problem of the model-based control strategy is the rapid growth of the size of the control state space, as more control variables with multiple possible attributes are to be considered. Assume a space with n control variables that can have values from s_1 to s_n. The total number, Z, of combinations of the values of these variables (i.e. the number of necessary simulation runs at each time step for an exhaustive modeling of the entire control state space) is thus given by:

$$Z = s_1 \cdot s_2 \cdot \ldots \cdot s_n \qquad [2]$$

The estimated number of necessary simulations to capture the entire control state space for the SAB test-cell is about 200 million for each time step. Even if we limit the exploration to just three possible attributes for each control variable, still about 60000 simulations would be necessary to derive the preferable control option. Obviously such numbers are beyond the computational capacity of currently available systems. To solve this problem, we intend to explore multiple approaches.

A hybrid model and rule-based approach

Prior to exhaustive simulation of the theoretically possible control options, rules may be applied to reduce the size of the control state space to one of practical relevance. Such rules may be based on heuristic and logical reasoning. A trivial example of rules that would reduce the size of the control state space would be to exclude daylight control options (and the corresponding simulation runs) during the night-time operation of buildings' energy systems.

The compartmentalization approach

Another approach to address the combinatorial problem described above is compartmentalization. The idea is similar to the methods used in CFD analysis of large domains. Instead of constructing a large detailed matrix, first a low-granularity matrix is established for the entire domain. Finer meshes are recursively generated and solved as needed. For model-based control, the compartmentalization can occur along two distinct dimensions, namely the spatial hierarchy and the domain spectrum. Figure 4 illustrates this two-dimensional compartmentalization scheme. This compartmentalized representation of buildings removes the necessity to perform whole-building simulations for every attribute of every control variable. Instead, the computational load for simulation could be distributed across the spatial hierarchy, or along the spectrum of various environmental control systems, or across a flexible mixture of these two dimensions.

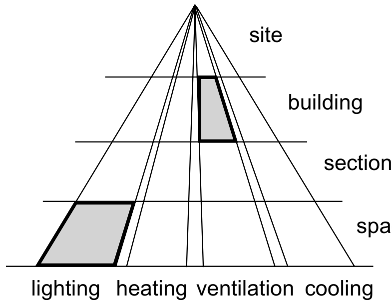

Figure 4: Schematic illustration of a two-dimensional compartmentalized hierarchy for model-based building systems control.

A greedy navigation technique for exploring the control state space

Via selection of efficient navigation strategies, the number of necessary parametric simulations at each time step can be reduced. This is independent of the scale at which a parametric simulations are performed (e.g., whole-building simulation versus space-level simulations). In order to illustrate this point, let us consider again the case of SAB test-cell. Table 4 summarizes, for this space, the control devices (control variables) and the number of states they can occupy.

Assuming exhaustive modeling, the total number of necessary simulations in this case would be $184 \cdot 10^6$ (cp. equation 2). Now, let us reduce the number of control variable states to three (the current state, plus the two adjacent states). To compute the total number of simulations in this case (Z_2), we must modify equation 2:

$$Z_2 = 3^n \qquad [3]$$

Since in the case of SAB cell n = 12, it follows that Z_2 = 531441. While this result represents a sizable reduction of the number of simulation, it is still too high to be of any practical relevance. Thus, to further reduce the number of simulations, we represent the control state space as a n-dimensional space, whereby each dimension represents a control variable. Assume the building to be at control state A at time t_1. To identify the control state B at time t_2, we scan the immediate region of the control state space around control state A. This we do by moving incrementally "up" and "down" along each dimension, while keeping the other coordinates constant. Obviously, the resulting number of simulations in this case (Z_3) is given by:

TABLE 4. Control variables and their discretization for SAB cell

Control variables	***Description***	***Number of states***
Lv	*Louvers*	8
L1	*Luminares*	10
L2	*Luminares*	10
L3	*Luminares*	10
L4	*Luminares*	10
Pem1-fl	*Air-flow, personal environmental module 1*	4
Pem1-t	*Temperature, personal environmental module 1*	3
Pem2-fl	*Air-flow, personal environmental module 2*	4
Pem2-t	*Temperature, personal environmental module 2*	3
WM	*Water mullion*	4
Win1	*Window 1*	2
Win2	*Window 2*	2

$$Z_3 = 2n+1 \qquad [4]$$

For SAB test-cell, $n = 12$. Thus, $Z_3 = 25$. Needless to say, this most recent number represents a significantly more manageable computational load.

Boundary conditions and random jumps

Continuous time-step modeling of the performance of building's systems is as such not a necessity. As long as the relevant boundary conditions of systems' operation have remained either unchanged or have changed only insignificantly, the building may remain in its previous state. Boundary conditions denote in this case factors such as outdoor air temperature, outdoor global horizontal irradiance, user request for change in an environmental condition, dynamic change in the utility charge price for electricity, etc. Periods of building operation without significant changes in such factors could not only reduce the need for simulation and thus the computational load, but also allow for the use of excess computational capacity toward the quasi-stochastic (e.g. monte-carlo based) exploration of more remote regions of the control state space. Such stochastic exploration could ostensibly increase the possibility of avoiding local minima and maxima in search for optimal control options.

7. CONCLUSIONS

As it stands, the SAB project has innolved the design and implementation of an experimental test-bed (SAB cell) toward development and evaluation of integrated multi-domain building control methods. While the initial testing of proptotypical model-based control approaches have been successful, future research must extend and refine these toward higher levels of modularity, flexibility, and scalability.

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