ENCLOSURE SYSTEMS DESIGN AND CONTROL SUPPORT VIA DYNAMIC SIMULATION-ASSISTED OPTIMIZATION

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ABSTRACT

This paper presents a computational environment for performance-based integrated building enclosure design and control support. The key concepts and features of this environment include: virtual enclosure, construction mapping, and shading device recommendation. Optimization methods are adapted and dynamically applied to derive the basic properties of a "virtual" enclosure for a given set of indoor climate requirements. These values are then mapped to a construction database to identify an actual building enclosure construction. The support for the real-time operation of the dynamic components of the building enclosure makes use of the time-step utilization of optimization methods. The functionality of the system is demonstrated via illustrative case studies.

INTRODUCTION

Building enclosure plays an essential role with regard to the overall performance of buildings. Specifically, energy performance, thermal comfort, and lighting conditions are significantly affected by the quality of enclosure design and its operational status. Previous research attempted to support the design of specific elements of building enclosure such as windows (Thiratrakoolchai 1986) as well as multiple parameters: U-value, solar transmittance, visible transmittance, glazing ratio, etc. (Jurovics et al. 1985, D'Cruz & Radford 1987, Bouchlaghem & Letherman 1990, Mathew & Mahdavi 1998, Pal & Mahdavi 1999). Most previous systems for optimal thermal performance usually consider only the illuminance level as the indicator of visual performance. Moreover, previous systems only help identifying the optimal material properties (i.e. thermal resistance, visible transmittance). Depending on this information, the user has to figure out what the actual enclosure should be. In addition, previous research studies did not address what the appropriate choice of shading devices (i.e. internal movable, external fixed, external movable) should be.

SYSTEM FUNCTIONALITY

The functionality of the proposed system is expected to: *a)* allow the user to explore different enclosure parameters; *b)* help identify the desirable material properties of building enclosure layers; *c)* retrieve appropriate enclosure components from a construction database; *d)* suggest appropriate shading devices; *e)* suggest an operation regime for the dynamic components of the building enclosure in response to thermal and visual performance criteria.

VIRTUAL ENCLOSURE

In this research, the facade is seen as a "virtual enclosure" which is an abstract representation of the relevant behavioral properties of the interface between indoor and outdoor environment (an "optimized" virtual enclosure allows for mapping into multiple possible (actual) realizations, depending on the applicable (e.g. locally available) repertoire of constructions). It consists of an opaque wall portion and a transparent (glazing) portion (Fig. 1). The opaque portion is modeled as a three layer composite wall. Each layer has two main properties, thermal resistance and thermal capacity. Thermal capacity (TC) is defined as the product of thickness, specific heat, and density. The glazing portion is specified in terms of thermal resistance, solar transmittance, and visible transmittance. The glazing percentage of the enclosure is also considered. In addition, the system will allow the user to control or modify the window geometry (proportion, position).

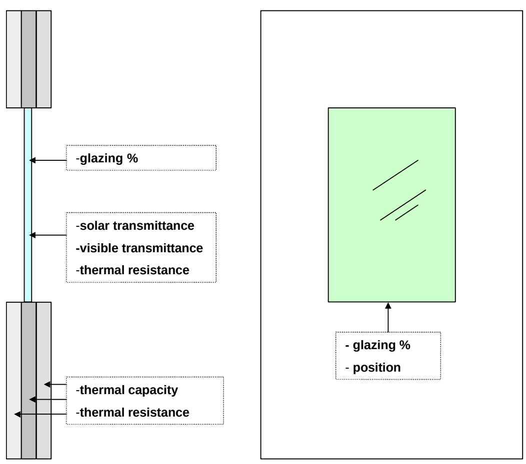

Figure 1: Parameters of the virtual enclosure

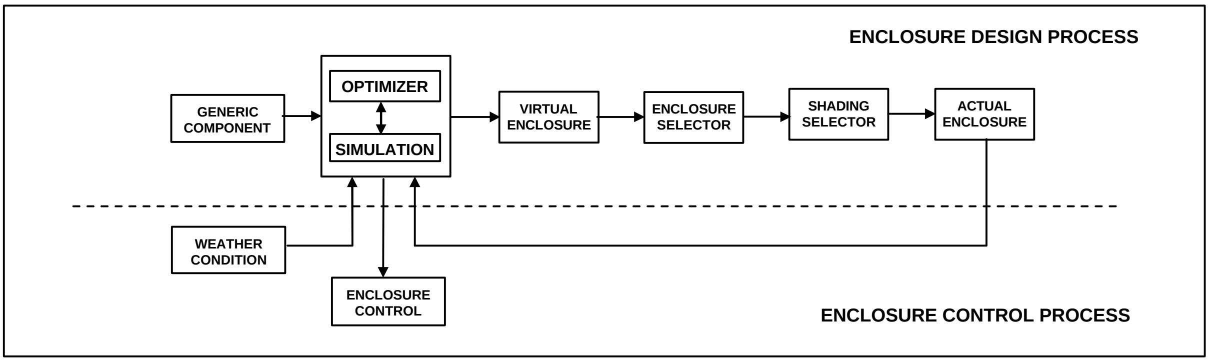

Figure 2: Proposed system functionality

SYSTEM IMPLEMENTATION

Overview

In order to support the aforementioned functionalities, the proposed system includes six main components (Fig. 2): *i)* thermal and visual simulation tools; *ii)* optimizer; *iii)* component database (wall, glazing); *iv)* enclosure selector; *v)* shading device selector; *vi)* graphical user interface.

A typical use case involves the following steps:

1. Virtual enclosure - This is an abstract representation of physical transfer phenomena and not a set of actual building layers. Optimization methods are adapted and dynamically applied to derive the basic physical properties of the enclosure (both opaque and transparent parts) for a given set of indoor climate requirements.
2. Enclosure Selection - The basic components of the building enclosure are determined in that the attributes of the optimal virtual enclosure are mapped to a database of actual building enclosure constructions.
3. Shading device selection - Using a knowledge-based mapping method, the "passive performance signature" of the basic enclosure configuration is used to derive recommendations for secondary enclosure devices for shading and light redirection.

The system can also be used for optimally controlling dynamic enclosure components (such as movable louvers) in order to provide the preferable visual and thermal performance at a specific time.

Simulation Tools

Thermal and visual performance simulation modules in SEMPER (Mahdavi 1999, Mahdavi et al. 1996) have been adopted for this research. These modules are NODEM (Mathew & Mahdavi 1998) for thermal simulation and LUMINA (Pal & Mahdavi 1999) for lighting simulation. NODEM is based on a transient heat balance method, whereas LUMINA is based on a hybrid radiosity and ray-tracing method.

In order to simulate the effect of daylighting on electrical lighting power consumption and thermal performance, the electrical lighting power consumption needs to be input in the thermal simulation tool. Therefore, the lighting and thermal applications must exchange data. LUMINA calculates the electric lighting power needed to make up the difference between the required illuminance and the available daylight.

Optimizer

Optimization methods – The criteria for choosing the optimization methods suitable for active design support are adapted from Mahdavi & Mathew (1995). These criteria are: *i)* the reliability of the algorithms used to predict the performance attributes *ii)* the transparency of the convergence process, and *iii)* the speed of computation and the state-to-state transition times. All optimization techniques discussed here can be used without simplifying thermal and visual performance evaluation methods. In addition, since all of them are based on iterative improvement, the processes of convergence are transparent. The optimization techniques that have been investigated are: *i)* Hillclimbing multi-restart (Russel & Norvig 1995); *ii)* Simulated-annealing (Kirkpatrick et al. 1983); *iii)* Hillclimbing with STAGE (Boyan 1998).

Objective functions – There are two main objective functions proposed in this research. For enclosure design, the building is considered in passive mode. The temperature profile for a whole year can be used to determine the appropriate shading device needed. The objective function for passive building is to maximize preferences for temperature as well as visual performance (illuminance, daylight glare index, and uniformity) (Equation 1). For buildings with HVAC, the objective function is to maximize energy and visual performance preferences (Equation 2).

$$OBJ_P = \frac{S_T W_T + S_E W_E + S_G W_G + S_U W_U}{W_T + W_E + W_G + W_U} \quad (1)$$

$$OBJ_A = \frac{S_L W_L + S_E W_E + S_G W_G + S_U W_U}{W_L + W_E + W_G + W_U} \quad (2)$$

where OBJ_P: objective function for passive building; OBJ_A: objective function for active building; S: preference score; W: weighting factor; T: temperature; L: energy load (heating, cooling, electrical); E: illuminance; G: daylight glare; U: uniformity.

Constraints – The following constrains are applied to reduce the search space, facilitate mapping from the virtual enclosure to real building constructions, and derive an appropriate window geometry:

1. Opaque wall - Minimum and maximum values of thermal resistance and thermal capacity are considered for each layer (to cater for the location of thermal mass, opaque walls are represented in virtual enclosure in terms of three layers, resulting in three sets of attributes). In addition, by considering the relation between thermal capacity and thermal resistance for building materials (Fig. 3), a constraint function was established. The search space, therefore, is limited to the region under the curve.

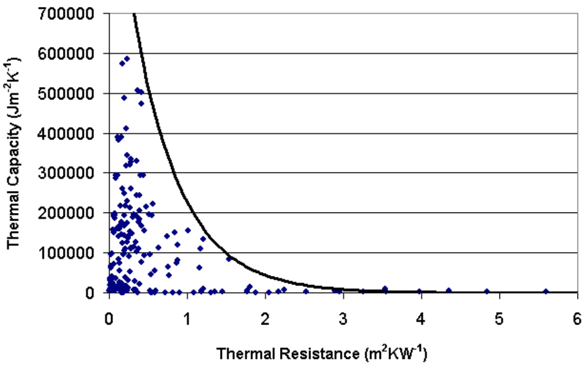

Figure 3: Constraint function for material properties of the layers

2. Glazing - Minimum and maximum values of glazing properties (thermal resistance, visible transmittance, and solar transmittance) are derived from glazing database.
3. Glazing percentage - During the optimization process, the glazing percentage of an enclosure is modified by adjusting the window dimensions. However, a new glazing percentage can not result in windows overlapping or moving out of a wall boundary.

Database

SEMPER provides multiple libraries that contain building information such as schedules, and construction types. The database used for this research has 201 material types, 97 wall construction types, and 207 glazing types.

Enclosure Selection

The optimum properties of the "opaque wall" and "glazing" components of the virtual enclosure are used to search for wall and glazing constructions in the database. However, since the real construction can have less or more than three layers, those layers must be aggregated or partitioned before comparison. "Thermal diffusivity" is used for appropriate aggregation. For a single layer construction, the layer is divided into three layers of equal thickness with the same thermal capacity and resistance. For two layers, the layer with the higher thermal diffusivity is divided into two layers. For a wall construction of more than three layers, all possible layer aggregations are considered and the one with the minimum average thermal diffusivity deviation is selected.

The most preferable wall construction or glazing is the one which has the minimum deviation of all properties from the optimum one (virtual enclosure). Since the impact of optimization parameters on the objective function may vary, the calculation of the deviation score for all optimized variables needs to be weighted. This is achieved based on the past optimization trajectories (Fig. 4). For each parameter a weight (W) is computed according to Equation 3. The wall construction properties' deviation is defined according to Equation 4, and glazing properties' deviation according to Equation 5.

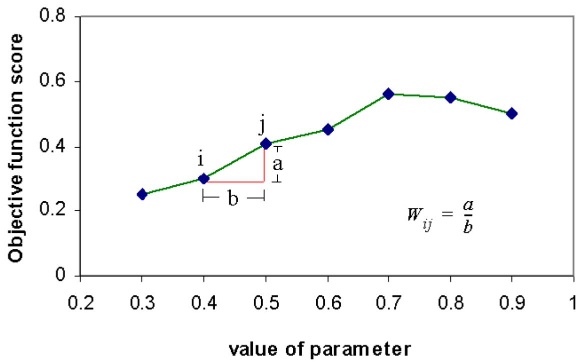

Figure 4: Demonstrative illustration of the effect of an optimization parameter on the objective function

$$W = \frac{1}{n}\sum_{i=1}^{n} \frac{|OBJ_j - OBJ_i|}{|V_j - V_i|} \quad (3)$$

where OBJ_i: previous objective score; OBJ_j: current objective score; V_i: previous parameter value; V_j: current parameter value; n: Optimization parameter value change frequency

$$D_W = |R1_O - R1_C| \cdot W_{R1} + |T1_O - T1_C| \cdot W_{T1} + |R2_O - R2_C| \cdot W_{R2} + |T2_O - T2_C| \cdot W_{T2} + |R3_O - R3_C| \cdot W_{R3} + |T3_O - T3_C| \cdot W_{T3} \quad (4)$$

where D_W: wall construction properties deviation; *R1*, *R2*, *R3*: thermal resistance of layers; *T1*, *T2*, *T3*: thermal capacity of layers; *o*: optimal property; *c*: compared property (from database); *W*: weighting factor

$$D_G = |R_O - R_C| \cdot W_R + |S_O - S_C| \cdot W_S + |V_O - V_C| \cdot W_V \quad (5)$$

where D_G: glazing properties deviation; R: glazing thermal resistance; S: glazing solar transmittance; V: glazing visible transmittance.

Shading device selection

The purpose of the shading device selection functionality is to find out: *i)* if a specific primary enclosure needs a shading device to achieve the desired thermal and visual performance, and *ii)* in case a shading device is needed, what type it should be.

Suppose the preferred temperature and illuminance in a space is defined in terms of preferred ranges (e.g. from t_{min} to t_{max} for temperature and from E_{min} to E_{max} for illuminance). According to these preference ranges, the results of both lighting and thermal simulation for every hour in a predefined time period can be categorized in terms of a number of discrete regions within a temperature-illuminance graph (see, for example, the regions A to I in Figure 5). Each point in each region represents an indoor condition (temperature, illuminance) at a specific time. By performing simulations in passive mode (without heating, cooling, and lighting system operation), the "natural" behavior of a building can be predicted and represented in the aforementioned graph.

Such a graph allows for formulation of general recommendations for the need for and the type of shading devices. An illustrative example of such recommendations is as follows:

1. No shading device is recommended for regions A, D, E, G, H. For E both temperature and illuminance are in the preferred range. For G, more solar gain and daylight is needed, therefore applying a shading device would not improve the performance of either. For H, more solar gain, and for D, more light would be desirable. The high temperature in A is unlikely to be the result of solar gains, given the low illuminance levels.
2. Interior movable shading device is suitable for I and F. An interior shading device allows solar gain to enter the space and thus improve the thermal performance in I. At the same time, an interior shading device can be adjusted to reduce excessive daylight penetration.
3. Fixed exterior shading device is more suitable for C, since an exterior shading device can reduce both solar heat gain and daylight penetration.
4. Movable external shading device may be more suitable for B. An exterior shading device can reduce solar heat gain. At the same time, it can be adjusted to control daylight penetration.

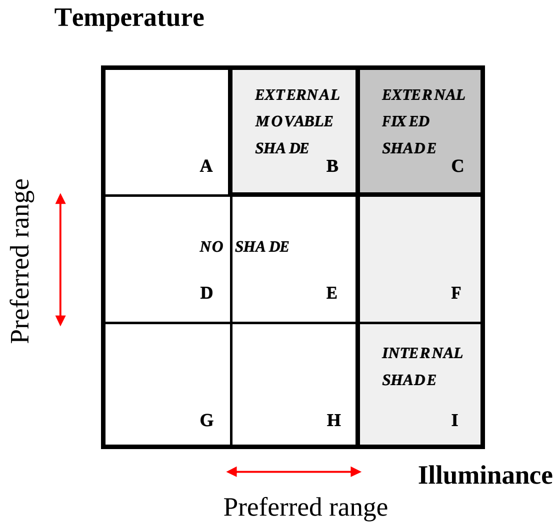

Figure 5. Shading device recommendation for each group of space conditions

However, the thermal and visual conditions calculated for every hour of the reference time period would be distributed in more than one region. Thus, applying a certain type of shading device could result in improved performance in some instances while worsening the performance in other instances. Therefore, the relative distribution of results in each region must be considered when selecting a shading device. To arrive at an aggregate recommendation, heuristic rules may be applied. An Illustrative instance of such rules is given in the following table (Table 1).

Table 1. Rules for shading recommendation

Shading Type	Condition
External (fixed)	[(B+C+F+I) > (A+D+E+G+H)] and [(B+C) > (F+I)]
Internal (movable)	(F+I) > 10% of all instances
External (movable)	[External (Fixed)] AND [(B > C)]
No shade	[NOT External (Fixed)] AND [NOT External (Movable)] AND [NOT Internal (Movable)]

Building Enclosure Control

Once a building enclosure has been designed, the system can be used for real-time control of external movable shading devices and electrical lighting.

During the optimization process, the current weather data is sent to both LUMINA and NODEM. The current dimming power of all luminaires and daylight coefficients (according to current louver position) is updated before LUMINA performs a simulation for the current time step. LUMINA sends the lighting power consumption to NODEM and also provides the system with the current visual performance output information (illuminance, glare index, uniformity). NODEM calculates the energy used for heating, cooling, and electricity (lighting and equipment). Illuminance, glare index, uniformity, and energy consumption data are used by the optimization program to compute the objective function. The best solution found from the optimization is used to set the current louver position and light dimming for the current time step.

Graphical User Interface

A user can input building geometry by drawing a plan on a canvas. The GUI provides default space properties (type, schedule, wall construction, glazing type and percentage) which can be modified by the user. The user can draw window geometry and external enclosure elements such as overhangs or louvers on the selected wall. In addition, the user can draw electrical lighting, occupant's viewing angle, and receiver points, and set the lighting properties (luminaire type, schedule, dimming curve). Data necessary for enclosure design and control optimization (e.g. optimization variables, performance variables considered in objective function) can be specified via GUI.

OPTIMIZATION SETTINGS

For all three algorithms, a new state is chosen by randomly selecting one of the optimization variables and then creating a perturbation in the value of this variable. The perturbation can be made by increasing or decreasing the current value. For hillclimbing, the perturbation direction is decided according to the previous direction that improved an objective function. For simulated annealing, since the previous state can be accepted even it does not improve the objective function, the perturbation is made by randomly increasing or decreasing the value.

Restart begins when the state reaches a local optimum (no optimization variable can improve objective function, either by increasing or decreasing its current value). The new restart point is made by random selection. The selected variables have to satisfy the previously mentioned constraints. For hillclimbing with STAGE, a new restart point is made according to a new restart state computed by the algorithm.

According to experimental results based on optimization settings described above, hillclimbing and hillclimbing with STAGE algorithms perform better than simulated annealing. However, for control purposes (where time is of essence) STAGE might be less suitable.

ILLUSTRATIVE CASE STUDIES

Overview

This section demonstrates the capabilities of the system. There are two main parts of the system: enclosure design and enclosure control. Enclosure design demonstrates three main functions: virtual enclosure optimization, enclosure selection, and shading device selection.

Enclosure Design

Case description – Consider a 10 x 6 m office in a commercial building (Fig. 6). There are three relevant enclosures (E0, E1, E2). Floor, roof, and interior wall (E3) are considered to be adiabatic. Passive building operation is assumed. NODEM and LUMINA are used for simulating thermal and visual performance. The lighting system can be dimmed to maintain an average illuminance at 550 lx. The light power calculated by LUMINA for every time step (1 hour) is used by NODEM. During the optimization process, glazing percentage is adjusted by increasing or decreasing window's width and height. The performance variable values and corresponding weights are shown in Table 2. The optimization variables are listed in Table 3.

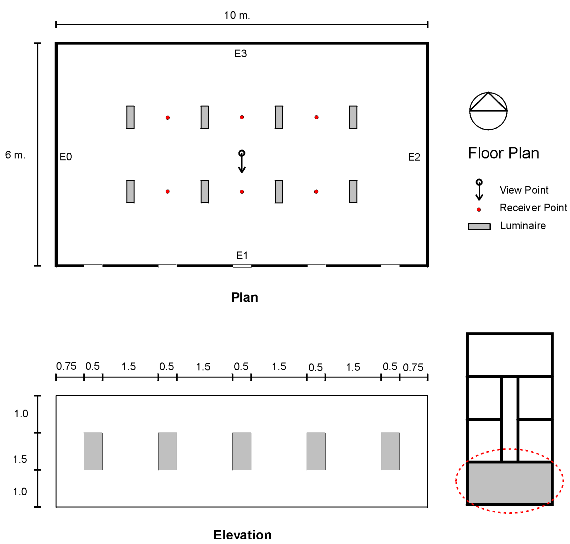

Figure 6. Description of the test case configuration

Table 2. Illustrative performance variable values and corresponding weights for design and control

Performance Variable	Weight	Performance variable scale and normalized score									
1. Temperature (^{0}C)	1.0	5 0.00	11 0.25	16 0.50	20 0.75	23 1.00	26 0.75	30 0.50	35 0.25	41 0.00	
2. Illuminance (lx)	0.5	0 0.00	100 0.10	300 0.50	500 0.80	1000 1.00	2000 0.80	3000 0.50	4000 0.25	5000 0.00	
3. Daylight Glare (-)	0.3	0 1.00	16 0.60	18 0.50	20 0.40	22 0.30	24 0.20	26 0.10	28 0.00		
4. Uniformity (-)	0.2	0 0.00	0.25 0.25	0.50 0.50	0.75 0.75	1.0 1.00					
5. Energy Load (Whm^{-2}) (for 15 minutes)	1.0	60 1.00	80 0.90	100 0.80	120 0.70	140 0.60	160 0.50	180 0.40	200 0.30	220 0.20	240 0.00

Variables 1, 2, 3, 4 are for enclosure design. Variables 2, 3, 4, 5 are for enclosure control.

Table 3. Settings for optimization of enclosure variables

Enclosure	Variable	Initial	Min	Max	Perturbation
0,1,2	R1	0.03	0.00003	1.79	0.20
0,1,2	R2	0.18	0.00003	1.79	0.20
0,1,2	R3	0.04	0.00003	1.79	0.20
0,1,2	TC1	25,610	120	597,839	5000
0,1,2	TC2	95,235	120	597,839	5000
0,1,2	TC3	39,345	120	597,839	5000
1	G-VT	0.10	0.05	0.95	0.10
1	G-ST	0.10	0.03	0.90	0.10
1	G-R	0.19	0.15	1.50	0.20
1	G-%	8.33	10	90	5

Virtual enclosure – Table 4 shows the optimization result of the "virtual enclosure" using a hillclimbing algorithm. For this example, the total number of function evaluations is set at 150. Figure 7 displays the progress of an optimization run. The initial objective score is 0.4515. The maximum objective score is 0.7510. The objective score is improved by increasing all design variables' values except wall TC2 and TC3. During the optimization process a user can see the simulation results for both thermal and visual performance (temperature, illuminance, glare index, uniformity). Figure 8 shows the elevation of the virtual enclosure.

Table 4. Optimization results using hillclimbing

Optimized Variables	Initial Value	Virtual Enclosure	Real Construction
R1	0.03	0.78	0.38
R2	0.18	1.79	1.18
R3	0.04	1.76	0.04
TC1	25,610	211,432	216,362
TC2	95,235	18,015	1,363
TC3	39,345	1,253	39,345
G-V	0.10	0.51	0.54
G-S	0.10	0.18	0.26
G-R	0.19	0.78	0.81
G-%	8.33	24.52	-
Objective score	0.4515	0.7510	0.7176

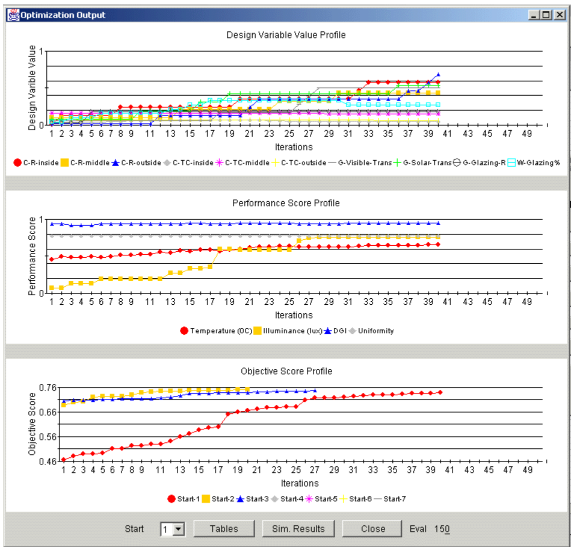

Figure 7. The progress of an optimization run: (top) optimization variable value (all values are scaled from 0-1), (middle) performance score of all performance variables, and (below) objective scores of each restart

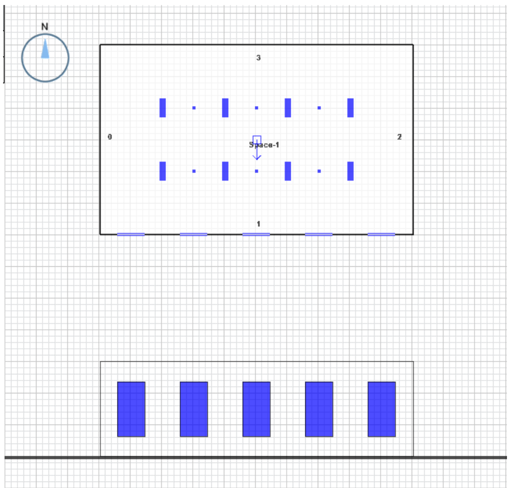

Figure 8. Virtual Enclosure Elevation

Enclosure selection – Once the virtual enclosure has been derived, the wall and glazing properties can be used to identify actual wall construction and glazing type. The user selects the preferred "virtual enclosure" by specifying the start and iteration number and the ranking number (Figure 9). The default start and iteration number is the one that has the highest objective function. The system searches for wall construction and glazing in the database. Once the search process is completed, the system generates a ranked list of possible wall constructions and glazing types. The user can then select which combinations are to be tested. The testing process is done by updating the properties of the walls and glazing, simulating thermal and visual performance, and calculating a new objective function. Table 4 shows the properties of wall and glazing selected from the database. Details of the wall and glazing are shown in Table 5.

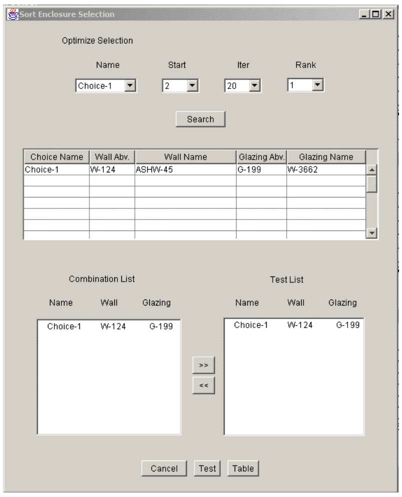

Figure 9. Wall and glazing search in the database

Table 5. Wall and glazing selected from the database

Wall (inside-outside)	Glazing
- plaster (20 mm) - clay tile (200 mm) - insulation (50 mm) - stucco (25 mm)	triple low-e clear insulating glass

Shading selection – Figure 10 shows a shading device recommendation. For this case, a movable interior shading device is recommended.

Enclosure Control

A 5 x 4 m office is considered in active operation mode (Figure 11). Temperature set points are 25 ^{0}C for cooling and 20 ^{0}C for heating. The lighting system can be dimmed. The time step for control is 15 minutes. The control variables are shown in Table 6. The performance scores are shown in Table 2. The system is used to find the best control option for dimming power and louver position according to the current weather condition. For testing purposes, Pittsburgh weather file is used.

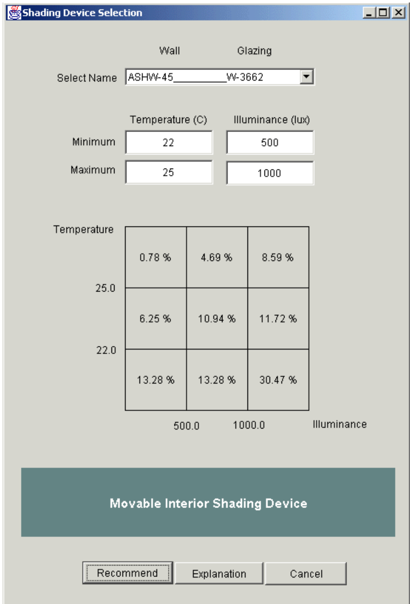

Figure 10. Shading device recommendation

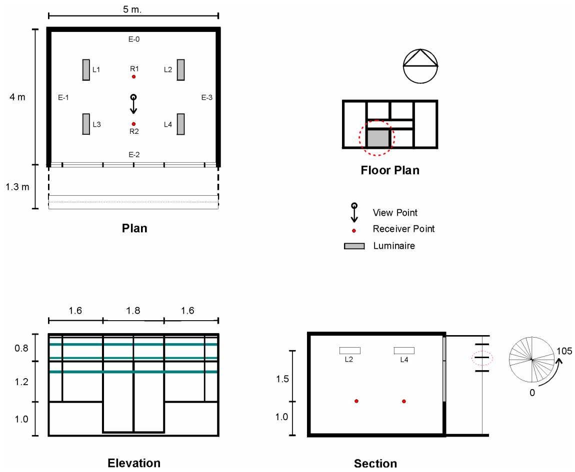

Figure 11. Configuration of the enclosure control

Table 6. Settings for optimization of device operation

Optimized Variable	Initial Value	Min	Max	Perturbation
Louver	90	0	105	15
Luminaire-1	1	0	1	0.1
Luminaire-2	1	0	1	0.1
Luminaire-3	1	0	1	0.1
Luminaire-4	1	0	1	0.1

To evaluate the performance of optimization method for control, the visual and thermal performance inside a space for three control options are compared (using objective function shown in Table 2):

1. Fixed louver position 90^0, luminaires dimming 1;
2. Fixed louver position 45^0, luminaires are automatically dimmed to maintain illuminance at 550 lx;
3. Louvers and luminaires are controlled by using hillclimbing multi-restart method.

The above settings are simulated for 9 to 5 pm (every 15 minutes) in December. The results show that by using an optimization method for control the objective score for both visual and thermal performance (Figure 12) can be improved over option 1 and 2.

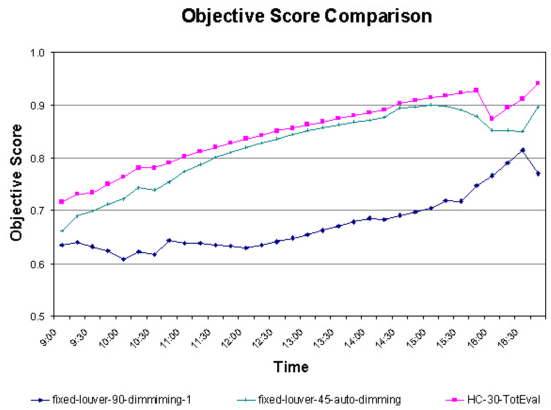

Figure 12. Objective scores comparison for three different options of louvers and luminaires

CONCLUSION

We presented a computational environment that uses building performance simulation and dynamic optimization to support the design and control of building enclosure systems. For a given context and desired indoor environmental (thermal and visual) conditions, the system derives the optimal properties of a virtual enclosure. These properties are then mapped to a construction database to select an actual enclosure system. Using the performance signature of the building in passive mode, a knowledge-based approach helps to decide if and what type of shading devices (internal, integral, external) would be desirable. Building enclosure operation support (real-time control of adjustable enclosure devices) is supported via dynamic utilization of the optimization tool. Future research must address additional features that are needed to accommodate queries pertaining to specialized constructions (e.g. double facades, active radiant enclosure configurations). In addition, a more comprehensive set of simulation applications are necessary to consider a richer set of performance indicators. Finally, the performance of the system in identification of optimal enclosure configurations and their control strategies must be documented on the basis of a more comprehensive validation study.

REFFERENCES

Bouchlaghem, N. M., Letherman, K. M. 1990. "Numerical Optimization Applied to the thermal Design of Buildings", Building and Environment 25(2): 117-224.

Boyan, J. A. 1998. "Learning Evaluation Functions for global optimization", Doctoral Thesis, School of Computer Science, Carnegie Mellon University.

D'Cruz, N. A., Radford, A. D. 1987. "A Multicriteria Model for Building Performance and Design", Building and Environment 22(3): 167-179.

Jurovics, S. A., Ho, C. H., Sorrell, F. Y. 1985. "New Energy-efficient Materials for the Building Envelope", Building and Environment 20(2): 95-101.

Kirkpatrick, S., Gelatt, C. D., Vecchi, M. P. 1983. "Optimization by Simulated Annealing", Science 222: 671-680.

Mahdavi, A., Mathew, P. 1995. "Implementation Strategies for Open Inference Design Environments", ICBEST'96 Conference, Strathclyde U.K.

Mahdavi, A., Brahme, R., Kumar, S., Liu, G., Mathew, P., Ries, R., Wong, N. H. 1996. On the Structure and Elements of SEMPER. Proceedings of the 1996 ACADIA conference. Tucson, Arizona, 71-84.

Mahdavi, A. 1999. "A Comprehensive Computational Environment for Performance based Reasoning in Building Design and Evaluation", Automation in Construction 8: 427-435.

Mathew, P., Mahdavi, A. 1998. "High-Resolution Thermal Modeling for Computational Building Design Assistance", Computing in Civil Engineering, Proceedings of the International Computing Congress, ASCE Annual Convention, 522-533.

Pal, V., Mahdavi, A. 1999. "A Comprehensive Approach to Modeling and Evaluating the Visual Environment in Buildings", Proceedings of Building Simulation'99, Sixth International IBPSA Conference, Kyoto Japan, 2: 579-586.

Russel, S., Norvig, P. 1995. "Artificial Intelligence: A Modern Approach", Prentice Hall, New Jersey.

Thiratrakoolchai, S. 1986. "Optimal Window Sizes for Minimum Thermal Loads of Vertical Exterior Walls at Specified Indoor Illuminances", Doctoral Thesis, School of Architecture, University of Michigan.