GUIDELINES FOR DEVELOPING A SIMULATION TOOL FOR EVALUATION OF FACADE DESIGN OPTIONS

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ABSTRACT

Fenestration and shading systems have a major impact on building thermal loads, energy consumption, as well as on visual and thermal comfort. For office spaces, the need for much daylight is often in conflict with the need to minimize cooling demand. This paper presents a simulation method that allows evaluation of shading design alternatives with respect to energy efficiency. The analysis includes a continuous parametric study of each shading device property depending on shading type, orientation and climate. Consideration of dynamic operation of facades in conjunction with lighting and HVAC system components is necessary and could help designers make important decisions at the early design stage.

INTRODUCTION

Fenestration area in commercial buildings is continuously increasing, driven by the higher demand for daylit buildings. Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting and cooling (Lee et al., 1998, Tzempelikos & Athienitis, 2005); the benefits in terms of higher productivity of office workers are also high (Heschong, 2002). Nevertheless, one has to take into account the balance between positive and negative impact of solar radiation on building overall energy performance and human comfort. Glass facades often create problems such as glare, thermal discomfort and overheating. Depending on the amount of thermal mass present, heating and cooling load could highly vary throughout the year for many locations. For all these reasons, many innovative fenestration and shading systems have been developed and studied in order to control solar gains, reduce glare and create a high quality indoor environment. These include advanced daylighting systems (prismatic panes, sun ducts, holographic elements, re-directing devices), glazing systems (electrochromic, thermotropic, gasochromic) and shading devices (roller shades, screens, venetian blinds, etc.). The optical and thermal properties of such systems are not usually provided by the manufacturers and thus have to be estimated using experimental techniques, complex theoretical models or advanced software (Reinhart et al., 2001). Tools like WINDOW (LBNL, 2003), WIS (van Dijk, 2002) and Parasol (Wall & Bullow-Hube, 2002) also provide valuable sources of measured data for a variety of glazing and shading products. Moreover, recent developments in dynamic building envelope technologies (i.e., airflow windows) have created new energy-efficient opportunities to achieve significant savings in building energy and peak demand, with enhanced occupant satisfaction. Coupled with electric lighting control systems, dynamic envelope and lighting systems can be actively controlled on a small time step to reduce the largest contributors to commercial building energy consumption: lighting and cooling due to internal gains.

Therefore the building design team has to choose from a wide variety of design options, for many of which the evaluation of their impact on building performance is difficult or even impossible. Inevitably, the selection of final design solutions often involves many subjective factors. Since the façade design relates to different aspects of building performance (heating, cooling, lighting) and human comfort (thermal, visual), an integrated approach should be followed from the early design stage. The significance of integration in building simulation is well explained by Citherlet et al. (2001). The realisation of the need for detailed simulation programs that integrate thermal and daylighting performance resulted in efforts in trying to couple daylighting and thermal simulation (Franzetti at al., 2004). A significant step was the development of performances on glazing systems based on integrated simulation (Citherlet & Scartezzini, 2003). However, the potential for dynamic operation of shading devices is generally neglected. The impact of shading design and control on building performance is not taken into account in the design stage, although an optimum cooling and lighting energy balance between fenestration and lighting may be identified and utilised (Lee & Selkowitz, 1995). Recent studies have shown that, appropriate shading design and control, when linked with simultaneous control of electric lighting and HVAC components, could significantly reduce peak cooling load and energy consumption for lighting and cooling, while maintaining good thermal and lighting interior conditions (Tzempelikos & Athienitis, 2003, Johnson et al., 1984). However, this is only possible by carefully selecting fenestration and shading properties and control, taking into account their combined impact on lighting and thermal performance of perimeter spaces and then optimizing their operation.

SIMULATION IN THE EARLY DESIGN STAGE

During the early design stage, the building geometry, characteristics and materials are still being formulated. Therefore the simulation approach should not be the analysis of a specific design solution, but the systematic exploration of inter-related design alternatives, in order to provide the building designer with a set of efficient design solutions. In general, there is less interest in finding "optimal" design solutions in the strict sense of the word (Mahdavi, 2004). Performance-based design support environments can be used in a flexible, dynamic and iterative manner. Moreover, optimization methods cannot be considered as design support tools, since they only produce optimal values. The objective of the design process is not generation of unique solutions; it should be a multi-level integrated process. For perimeter spaces, the simulation procedure in the early stage should be able to take into account daylighting and thermal parameters, link them in an integrated way, and provide a method for quantitative and qualitative evaluation of design options based on performance-based measures. Therefore, different building system aspects (daylighting, electric lighting, heating, cooling, shading) have to be considered simultaneously when making early stage decisions. The transition from component-based simulation to a "systems" approach is a key issue for an integrated design process.

Presently, building performance can be accurately predicted using advanced energy simulation programs. Some of them (i.e. ESP-r, Energy Plus) link daylighting and thermal simulation in an integrated manner (Clarke et al., 1998). However, a separation must be made between the processes of simulation analysis and design. The main problem is that the current integrated building simulation software are used to evaluate the overall energy performance of existing buildings, or expectantly, in the design development stage, when the building form is already determined. An advanced simulation tool can predict the thermal and lighting performance of a perimeter space for a specific fenestration solution. However, it cannot provide useful information on how (and why) to select design alternatives, since all such software require detailed input data to run even the simplest simulation, and these data are not yet available at the early design stage. Consequently, the selection of final design solutions concerning fenestration often involves many subjective factors imposed by the design team at the early stage. In reality, advanced building simulation programs are used to "optimise" design solutions selected on a subjective basis at the conceptual design stage. A gap between the potential benefits claimed for daylit buildings and the actual achievement in building practice still remains.

The following sections describe the simulation methodology developed for daylighting and thermal simulation, the coupling between the two using a simulation tool and the extraction of useful information based on performance indices generated by the continuous interaction between the two domains. An important requirement is utilization of hourly or sub-hourly data that will be used for daily, monthly and yearly calculations. The simulation-based approach followed is to create generalized performance indices (at a systems level) as parametric functions of key design parameters (at a component level, such as the window area); then, use the tool to provide the designer with useful information for the selection of the desired value based on the integrated analysis results. It applies to perimeter spaces of commercial and institutional buildings (particularly private offices) for any location, orientation, glazing type and shading type.

THEORETICAL BASIS

Early stage design for perimeter spaces is essentially a systems integration challenge, involving all parameters connected to integrated daylighting and thermal performance. The key issue for coupling the two domains is to determine a set of linking parameters that have an impact on both the thermal and lighting performance of the space. The dynamic interaction between lighting and thermal simulation can then be described by investigating the relationship between these linking parameters and the simultaneous impact on the two domains during the actual simulation process.

An exploration of dynamic links between lighting and thermal performance leads to a distinction between direct and secondary links. Direct links have an immediate impact both on the daylighting and the thermal performance (e.g. amount of transmitted daylight and solar radiation). The following parameters were identified as direct dynamic links:

- Window-to-wall-ratio
- Window properties
- Shading device type and properties
- Shading device control

Secondary links work like transfer functions. They transfer the dynamic effect of the direct links to the other domain. A secondary dynamic link is the *electric lighting control*: for a given set of direct links, it operates by reading data from the daylighting module and dynamically transfers the effect of resulting internal gains to the thermal module. Finally, linking parameters are separated into continuous and discrete. Shading type and control and electric lighting control are discreet parameters because they can take certain values; in a way, they act like interactive boolean operators during the simulation process.

The interaction between the thermal and lighting simulation with the direct and secondary linking parameters is an iterative process. For instance, thermal and lighting simulation will run considering a continuous distribution function of direct continuous links and a set of values for discreet direct links, and values for linking parameters will be selected based on the results of integrated thermal and lighting simulation, taking into account variations in all other links. This iterative sensitivity analysis approach continues until desired values are computed for all parameters, using as measures correlations between generalized performance indices generated by the continuous interaction between the two domains during the actual simulation process. This dynamic process aims at providing the building designer with significant performance-based measures for making important decisions during the early design stage, using as basic criteria the following:

- Maximization of daylight utilization
- Elimination of glare, and visual comfort
- Reduction in peak thermal loads
- Reduction in energy consumption for heating and cooling
- Reduction in lighting energy consumption

Figure 1 summarizes the process of coupling and the interactions between linking parameters in the simulation methodology.

Integrated performance indices

The last step of the general methodology is to calculate certain "integrated performance indices". The purpose of these measures is to include useful information to help the designer compare design options on a relative basis. The definition of these parameters implies that the performance indices must have certain characteristics:

(i) A performance index must be generalized. It has to be a general parameter that includes the impact of climate and building characteristics so that the same unique index can be used to describe the overall performance of perimeter spaces of different form (e.g., different fenestration) and in different locations, for consistent comparison of measures.

(ii) Instead of giving a static picture of the conditions in a room, a performance index should contain all the necessary information for sufficient evaluation of the integrated performance of a space. For example, work plane illuminance is not an appropriate performance index since it changes with time. An efficient way to overcome this problem is to consider annual performance parameters and not values at particular times.

(iii) An integrated performance index is generated by the interactive simulation process and must include the combined impact of linking parameters on daylighting and thermal simulation. Moreover, it should not describe a specific component (or link) but should include their impacts on a systems level.

(iv) For a given set of direct and secondary links, each performance index is represented by a single numerical value. Thus, comparison of integrated performance of spaces could be made simply by comparing numbers. However, it is an objective of the current methodology to study the variations of integrated performance indices as a function of linking parameters, so that the designer can make decisions about selection of linking values based on the variation of performance indices. Moreover, correlations between two integrated performance indices could serve the same purpose on a different level, as discussed later.

The above characteristics provide the basis for choosing reliable performance-based measures. The following parameters have been selected as integrated performance indices:

- **Annual heating and cooling energy demand**. These are the most obvious measures, since they contain all the information used in the simulation process and they enclose the combined impact of all linking parameters. This is a general index used by all major simulation software to describe the energy performance of buildings.

- **Peak thermal loads**. Although this index does not characterize the annual energy performance of buildings, it is equally important because (i) during the early design stage it is the measure that determines the HVAC system size (and initial costs) and (ii) studying the dependence of this index on dynamic links for perimeter spaces can provide critical information about load characteristics.

- **Daylight availability ratio (DAR) or daylight autonomy.** There is a need for a generalized index that represents the overall daylighting efficiency in a space. Hourly work plane illuminance profiles are not an appropriate index, since they change continuously. A transformation from hourly values to an annual universal index was achieved using the concept of daylight availability ratio. This is defined as the fraction of time in one year during which sufficient daylight (more than a pre-specified set point) is available on the work plane imaginary surface. The advantages of using this measure are clear: (i) it is a general, time-independent index that fully describes the daylighting availability in a room, taking into account the yearly impact of all fenestration parameters and climate (ii) it provides all the necessary information for straight computation of electric lighting energy consumption. None of the existing building simulation software (except for

DAYSIM -Reinhart, 2005) provides such a useful index. Instead, tables/graphs of work plane illuminances are usually given as output.

Energy consumption for electric lighting. This is also a useful integrated performance index because it includes the impact of all direct linking parameters plus the secondary link of electric lighting control. Electricity consumption for lighting accounts for a large part of total energy consumption (30%-50%). Also, this index carries one of the impacts of daylighting (on which it depends) on the thermal performance by means of internal gains.

SIMULATION ANALYSIS

The Perez irradiance model and the luminous efficacy models (Perez et al., 1990) are used to calculate solar radiation and daylight incident on a façade. Then, depending on the optical properties of the windows, the work plane illuminance is computed, using one of the radiosity (Athienitis & Tzempelikos, 2002), ray-tracing or daylight coefficients method (Tregenza, 1983). The simulation model predicts 8760 values of work plane illuminance for each point, window-to-wall ratio and orientation. Daylight Availability Ratio (DAR) is computed next as a function of orientation and window-to-wall ratio (WWR) using automatic matrix operations with the predicted illuminance values.

For the thermal module, a thermal network approach is used. Convection and radiation are separated and can be modeled in different degrees of detail. Radiation between all interior surfaces is modeled using the radiosity method, using non-linear heat transfer coefficients. Heat storage in walls is modeled by placing thermal capacitances in thermal mass nodes. Solar gains are calculated in detail in order to accurately model the impact of climate and fenestration on interior conditions of perimeter spaces. The transmission of solar radiation in the room is done in the same way as for the daylight. Transient hourly values of window solar transmittance are calculated to be used in the thermal simulation model. The amount of heat captured in glazings and released to room air is also computed. In the case of a shading device, the level of modeling detail depends on the type, location and properties of shading. The shading device solar thermal properties are again estimated as a function of time, to consistently transfer their impact on interior conditions. Internal gains from lights, appliances and people are also modeled in detail, on an hourly basis. Occupancy and lighting operation schedules and time-based control of shading devices and other systems are all included in the simulation algorithm using an explicit form of the equations. This is a critical characteristic of the simulation process; it will reveal the effect of linking parameters on the integrated performance indices.

An energy balance is applied on each node at regular time steps, to obtain the temperature of the nodes as a function of time. When all thermal resistances and heat sources have been calculated, a simulation time-step (Δt) is selected based on a numerical stability criterion. Then all the hourly variables are evaluated for each time step, using a time series method or Fourier transform. The system of simultaneous differential and algebraic non-linear equations can be solved numerically using an explicit finite difference technique, in which we march forward in time from a set of initial conditions. The general form of the explicit finite difference model corresponding to node (i) and time step (p) is (Athienitis, 1994):

$$T_i^{p+1} = \frac{\Delta t}{C_i} \cdot \left\{ q_i + \sum_j \frac{(T_j^p - T_i^p)}{R_{ij}} \right\} + T_i^p \qquad (1)$$

where T is temperature, (p+1) indicates next time step, (j) all nodes connected to node (i), R_{ij} is the thermal resistance connecting nodes (i) and (j), C_i the capacitance of node (i), if any, and q is a heat source at node (i). Short time-step temperatures of all network nodes and room air are calculated using Eq. (1). Heating and cooling load is directly computed using an appropriate proportional control constant.

Window-to-wall ratio (glass ratio of a façade)

Window size is the most critical direct link affecting both daylighting and thermal performance of a perimeter space. The combined effect of window-to-wall-ratio on daylighting and thermal performance of perimeter spaces is investigated by using window area as a continuous design variable in the thermal and daylighting modules for each orientation and for different sets of secondary link options (electric lighting control). Then integrated performance indices are computed considering window-to-wall ratio as a design parameter. Plots of annual daylight availability ratio for each orientation show the effect of a dynamic link in the first performance index. Electricity consumption for lighting is calculated simultaneously as a function of window-to-wall ratio for different lighting control strategies (passive, on/off, dimming). Therefore a second performance index is calculated including the combined effects of a direct and a secondary link. Daylight availability increases for higher window-to-wall ratios, therefore lighting energy consumption is reduced depending on the control mode. Electricity demand for lighting can be directly calculated directly from the daylight availability ratio as a function of window-to-wall ratio (Tzempelikos & Athienitis, 2004). This performance index provides a secondary measure for quantifying the effect of daylight utilization on energy consumption. Reduction in artificial lighting operation results in the reduction in internal gains and thus a reduction in cooling requirements. Thermal simulation runs simultaneously and plots the remaining performance indices as a function of the design variable (WWR), taking into account the impact of electric lighting operation on thermal loads. The procedure is summarized in Figure 2.

A schematic of the expected impact of window-to-wall ratio on the general space performance (i.e., daylighting, lighting and thermal) is possible by plotting integrated performance indices as a function of WWR (Figure 3). The building designer can then evaluate the integrated performance characteristics for the studied design parameter for each orientation. For an active lighting control strategy, the impact on cooling demand is inverse: the part of cooling load that results from internal lighting gains decreases for higher window-to-wall ratios because electric lighting operation is reduced for larger window areas. Yet solar and heat gains are usually higher and this is the reason that cooling load is likely to increase for larger window areas. Morover, there is a WWR "region" beyond which further increase in window size does not contribute to daylight availability (shadowed region between the two parallel lines). This is identified as "saturation" of useful daylight (Johnson et al., 1984).

Shading

Shading devices are essentially the second direct dynamic link between daylighting and thermal performance of perimeter spaces. Their type, properties and control have a significant impact on daylighting and thermal interior conditions. Peak thermal loads, energy demand and electricity consumption for lighting strongly depend on shading parameters. A second round of the integrated design methodology is therefore necessary for computation of the general performance-based measures, considering shading variables as design parameters. Due to the complexity of the problem, this approach is not followed by any existing design/simulation software, although the benefits are obvious: the designer is provided with all the required information, taking into account interactions between thermal and daylighting analysis, for selecting appropriate shading system characteristics for each case.

Shading device type

The selection of shading system generally depends on the type of building, architectural aesthetics, climate, orientation, functionality and cost. Shading can be placed exterior, interior, or in some cases, inside the window cavity (between glass panes). That would be determined primarily based on climatic conditions. For example, it would be reasonable to assume that in a cooling-dominated climate shading devices should be placed outside in order to reject as much solar heat as possible. More sophisticated systems such as double skin facades or airflow windows with intermediate shading between the two glass panes could be applied to a wide variety of climates. Following the technological advancement in building envelopes, movable and controlled shading can be used for better performance. In practice, two main types of shading devices are used in office buildings presently- roller shades and venetian blinds.

Shading device optical and thermal properties

For any kind of shading system, its optical and thermal properties would initially determine the overall impact of shading on the interior. Visible (daylight) and solar transmittance, reflectance and absorptance, as well as shading thermal resistance, are major parameters that will determine thermal and lighting performance. Orientation, type and location of the shading device affect the selection of shading properties obtained by the integrated daylighting and thermal analysis. Advanced building simulation software can import shading properties from existing databases for certain products but this approach only allows evaluation of the performance of a specific product with particular characteristics. What the designer needs is a general estimation of the impact of shading properties on performance assessment indices, considering shading as a design parameter.

For each type of shading, integrated performance indices are calculated as a function of shading properties for each orientation during the simulation process. The combined impact of shading optical properties on daylight availability ratio and electricity consumption for lighting is computed in conjunction with the effect of shading solar and thermal properties on heating and cooling demand and peak thermal loads. Furthermore, the secondary link of electric lighting control allows investigation of the impact of shading optical properties on thermal performance indices. Shading properties as design variables provide a means for evaluation of the complex interactions between the thermal and lighting domains of the building system at an advanced level. For a complete analysis, one final basic direct link has to be simultaneously considered: the control of the shading device.

Shading device control

Motorized shading devices can operate based on different criteria: maximization of daylight, minimization of thermal loads, reduction of glare, thermal comfort, etc. There is no standard in selecting control criteria; usually, the shading device is controlled based on glare index values (Lee & Selkowitz, 1995) or transmitted/incident beam radiation (Reinhart & Jones, 2004). Sophisticated methods exist for control of venetian blinds and prediction of indoor illuminances based on correlations between calibrated interior sensors (Park & Athienitis, 2003, 2004).

The selection of control strategy plays a major role in the determination of interior conditions. For office spaces, it is suggested that direct sunlight is not allowed to enter the room, in order to prevent overheating and glare problems. That means that venetian blinds must rotate to block sun's rays and roller shades must close to allow only diffuse light into the room. Climatic conditions and daylight availability play a major role in the design and control of a shading system. The type and location of the shading also have to be considered simultaneously. For example, for a hot climate, priority could be given in cooling load reduction. This translates into low effective transmittance and development of a control algorithm for rejection of solar gains. In the case of overcast climates, another strategy should be employed to simultaneously allow daylight maximization.

Furthermore, in order to be consistent with the philosophy of this integrated design methodology, the type of control strategy used has to be decided simultaneously with the selection of its optical and thermal properties for each type of shading device used and for each orientation. This realization is a key point for a successful integrated design. Shading device properties and control (second stage direct dynamic links) are now considered as design variables. Integrated performance indices are computed as a function of shading properties for different options of shading control. Shading control has a direct impact on the daylighting and thermal performance, on electricity consumption for lighting, and an indirect impact on thermal conditions, because it affects electric lighting control operation and thus internal gains. The process is summarized in Figure. 4.

The variation of integrated performance indices with shading variables (e.g. optical properties) allows extraction of design solutions based on an overall space performance assessment. The designer evaluates the impact of each variable and can make appropriate decisions for each orientation, combining the analysis results with other architectural constraints. Figure 5 shows the case for shade transmittance, which is considered a continuous variable in the simulation. The simultaneous impact of different shading control and electric lighting options is shown in the same graph in order to select a matching control strategy at the same time. The curves of Fig. 5 reveal critical information concerning the integrated space performance. Optimum energy performance is achieved when daylighting benefits due to reduced electric lighting operation and also due to reduction in cooling load (due to decreased lighting operation and shading control) exceed the increase in energy demand due to increased solar gains. Therefore a combination between two performance indices was identified as a key indicator: the sum of lighting and cooling energy demand (the sum of energy consumption could also be an indicator). For specific shading control strategies, it is possible that this index is minimized. Maximization of daylight is considered as a criterion in this stage also; the energy performance of shading should not take priority over the daylighting requirements. For example, choosing a very low shading transmittance combined with a conservative control would eliminate daylight availability. A balance between the two is proposed when selecting shading properties and control, and this can be achieved using a three-section façade (Tzempelikos & Athienitis, 2003).

CONCLUSION

Advanced building simulation software cannot provide guidelines for selecting fenestration and shading solutions from the early design stage- when important decisions are made that have a significant impact on the building performance. Since the façade design relates to different aspects of building performance (heating, cooling, lighting) and human comfort (thermal, visual), an integrated approach should be followed from the early design stage. This paper presented the basis for development of a simulation tool for evaluation of façade design options, linking daylighting and thermal simulation. The basic step for developing an integrated and systematic daylighting and thermal design methodology is to consider fenestration properties as design variables in a coupled thermal and daylighting simulation model. The major links between daylighting and thermal performance were identified as (i) window-to-wall ratio (ii) glazing type (iii) shading device optical and thermal properties (iv) shading control and (v) electric lighting control as a secondary link. These parameters provide a means for simulating the interactions between daylighting and thermal performance and were used as design variables. Generalized integrated performance-based measures are then calculated from the coupled daylighting and thermal simulation results. These indices included the impact of climate, fenestration system properties and control and electric lighting control and enclose the combined effects of linking parameters in the integrated design process.

Optimum energy performance can be achieved if daylighting benefits, due to the reduction in lighting energy demand and subsequent decrease in cooling load and demand, exceed the increase in energy demand due to increased solar gains. Appropriate selection of shading device properties and control, in conjunction with artificial lighting control can make this possible. At the same time, other benefits of daylighting (e.g. increase of occupant productivity) have to be considered simultaneously, by studying the effect of design variables on the daylighting performance index, named Daylight Availability Ratio, and make decisions based on daylight "saturation" regions. Innovative fenestration systems should be taken into consideration from the early design stage, since they have a potential for satisfying the above requirements, and compared on a relative basis with other solutions.

Recent studies have revealed that occupants would rather want to have some control over their luminous environment. Although manual operation of shading would not achieve the goals set in this methodology, it is useful to consider the simulation of manual control of shading and lighting systems for a more realistic representation on the actual perimeter space performance. Finally, the extension and implementation of the integrated daylighting and thermal design methodology, including ventilation, in one of the existing advanced building simulation software packages would create the potential of using these tools for design and not only for simulation. A dual use of an advanced building simulation tool (i.e., for design purpose and for simulation purposes) would fill the gap, still remaining today, in assessing and evaluating overall building performance from the early design stage.

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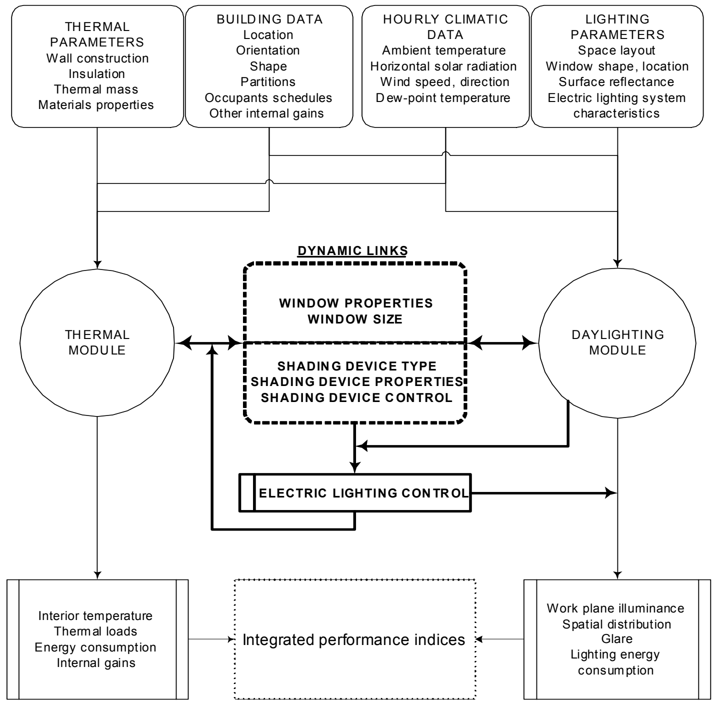

Fig. 1. Process of coupled daylighting and thermal simulation and the interaction with dynamic links.

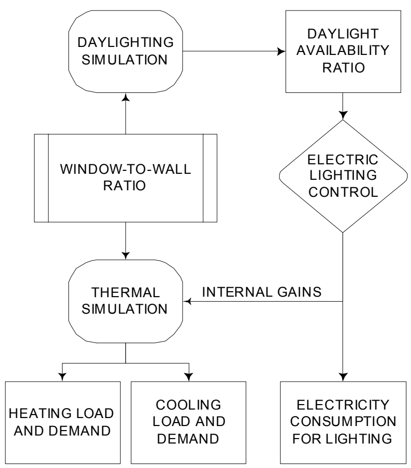

Fig. 2. WWR as a design variable in the simulation

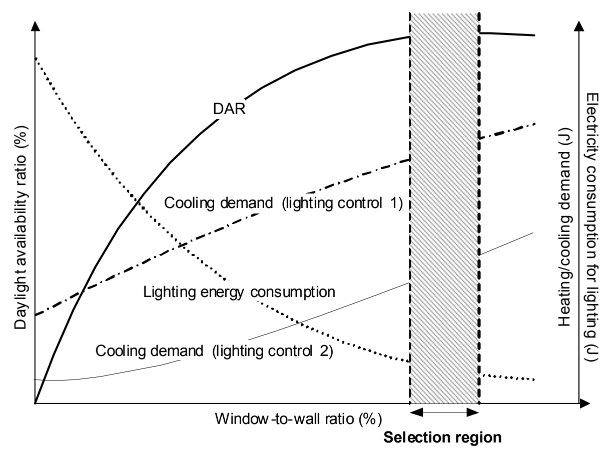

Fig. 3. Expected variation of performance indices as a function of WWR.

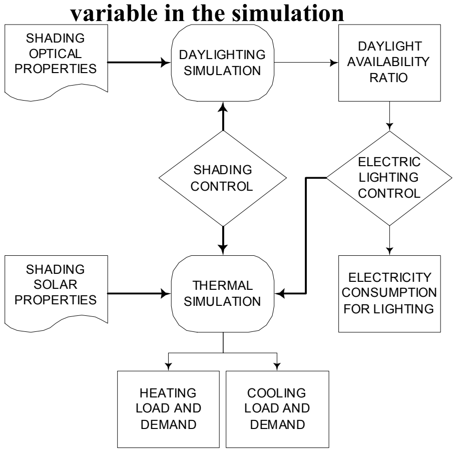

Fig. 4. Simulation flowchart that summarizes the integrated design analysis. The interactions between daylighting and thermal performance are described using shading properties and control links as design variables.

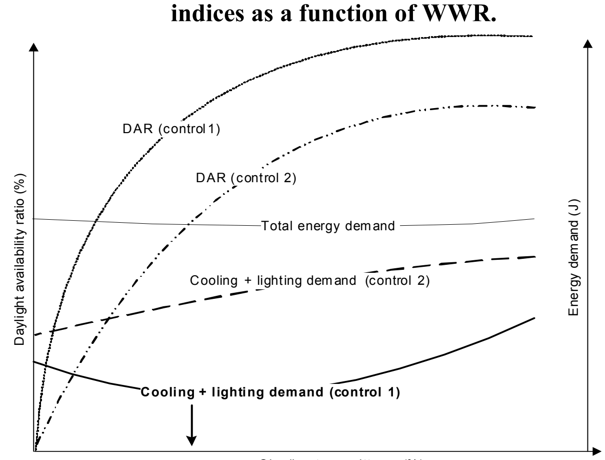

Fig. 5. Expected variation of integrated performance measures as a function of direct shading links which are considered design variables