Shading as an active component for solar control: an integrated approach at the early design stage

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ABSTRACT: The need to control solar gains is often in conflict with the need to satisfy daylighting requirements. Utilization of daylight could reduce electricity consumption for lighting and increase occupants' productivity. On the other hand, admission of excessive solar gains could result in increased cooling energy demand. Therefore shading provision should be considered as an essential part of fenestration system design from the beginning of the design process. Glass area, shading properties and control have a major impact on the building energy performance as well as on human comfort. This paper presents an integrated approach for design of facades and perimeter spaces, taking into consideration daylighting and thermal issues. Such an approach at the early design stage could help architects and designers make important decisions that will have significant weight during the lifetime of a building.

Keywords: design, façade, daylight, shading, lighting, energy

1. INTRODUCTION

The design and control of facades and fenestration systems has a major impact on building performance, especially for perimeter spaces of commercial and institutional buildings. With the growing interest in energy-conscious design and solar architecture, the importance attached to daylight utilization has grown: nowadays, daylighting is essentially a necessity for commercial buildings. Moreover, recent developments in dynamic building envelope technologies have created new energy-efficient opportunities to achieve significant savings in building energy, peak demand, and cost, with enhanced occupant satisfaction. Coupled with electric lighting control systems, dynamic envelope can be actively controlled on a small time step to reduce the largest contributors to commercial building energy consumption: lighting and cooling. 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 and fenestration 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. Clarke et al. (1998) explains well the significance of integration in building simulation. The identification of the need for detailed simulation programs that integrate thermal and daylighting performance [1] resulted in efforts in trying to couple daylighting and thermal simulation [2]. A significant step was the development of performances on glazing systems based on integrated simulation [3]. A prototype method on design optimization for glazing performance was presented by Johnson et al. (1984). In an integrated lighting and thermal simulation study with emphasis on the comfort aspect [4], the window transparency is identified as the link between thermal and visual performance. A more complete parametric study [5] set the basis for design of low energy office buildings.

However, the impact of dynamic shading operation on building performance is generally not taken into account in the design stage, although an optimum cooling and lighting energy balance between fenestration and lighting may be identified and utilized [6]. Herkel [7] correctly identifies shading control as an important interactive link between daylighting and thermal simulation. Recent studies have shown that shading operation, 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 interior conditions [8]. However, this is only possible by carefully selecting fenestration and shading properties and control, taking into accounts their combined impact on lighting and thermal performance and then optimizing their operation. The main problem is that the current integrated building simulation software are used to evaluate the energy performance of existing buildings, or expectantly, when the building form is already determined. That is because detailed input data is required in order to run even the simplest simulation. Consequently, the selection of final design solutions concerning fenestration often involves many subjective factors imposed by the design team at the early stage.

2. INTEGRATED SIMULATION AT THE EARLY DESIGN STAGE

2.1 Simulation for early design

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 [9]. Performance-based design support environments can be used in a flexible, dynamic and iterative manner. 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 evaluation of design options based on performance-based measures.

The following sections describe the simulation methodology developed for daylighting and thermal simulation, the coupling between the two using simulation and the extraction of useful information based on performance indices generated by the continuous interaction between the two domains. 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 for any location and orientation.

2.2 Methodology

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. 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.

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, using the following as basic criteria:

- 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

Finally, an important 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. Therefore they have to be generalized, time independent parameters that enclose the impact of simultaneous thermal and daylighting simulation:

- Annual energy demand for heating/cooling
- Peak thermal loads
- Daylight Availability Ratio
- Energy consumption for electric lighting

The Daylight Availability Ratio (DAR) 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: 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.

2.3 Exploration of dynamic links
Window-to-wall ratio (WWR)

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. 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. Electricity demand for lighting can be directly calculated from the daylight availability ratio as a

function of window-to-wall ratio [10]. 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. 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 1). The building designer can then evaluate the integrated performance characteristics for the studied design parameter for each orientation. 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.
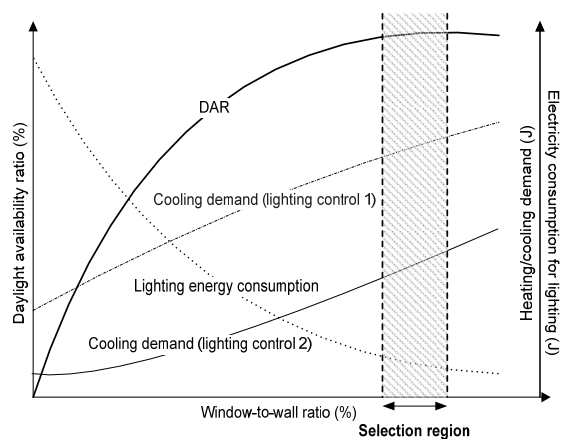
Figure 1: Impact of a design parameter (WWR) on the integrated performance indices.

Shading device optical and thermal properties

Shading devices are essentially the second direct dynamic link between daylighting and thermal performance of perimeter spaces. 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.

For each type of shading, integrated performance indices are calculated as a function of shading properties for each orientation. 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. For a complete analysis, one final basic direct link has yet to be 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 [6] or transmitted/incident beam radiation [11]. Sophisticated methods exist for control of venetian blinds and prediction of indoor illuminances based on correlations between calibrated interior sensors [12].

The selection of control strategy significantly affects 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. Climatic conditions and daylight availability play a major role in the design and control of a shading system. For example, for a hot climate, priority could be given in cooling load reduction.

Furthermore, in order to be consistent with the 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 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. The process is summarized in Figure 2.
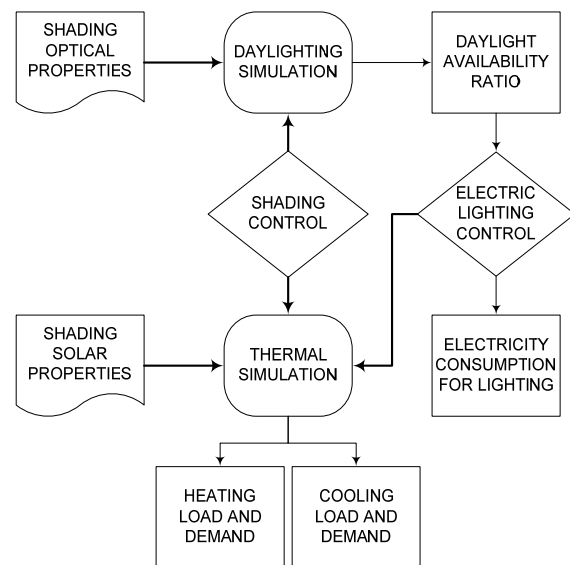
Figure 2: The integrated analysis with shading design parameters

The variation of integrated performance indices with shading variables (e.g. optical properties) allows extraction of design solutions. 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 3 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. 3 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. 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; a balance between the two is proposed when selecting shading properties and control, and this can be achieved using a three-section façade [8].
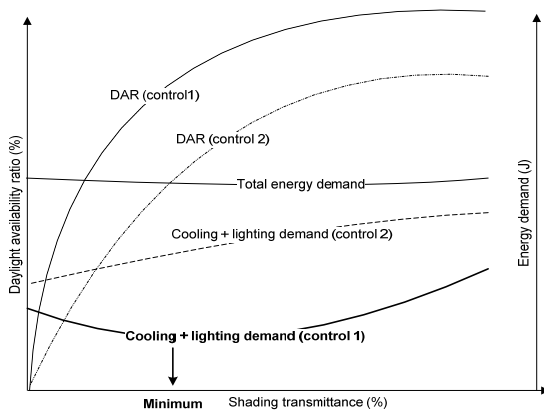

Figure 3: The impact of shade transmittance on performance indices.

3. RESULTS

The methodology was applied to a case study institutional building in Montreal, in order to estimate the impact of shading on perimeter zones performance. Glazing R-value, lighting and shading controls were considered as design variables. The impact of window-to-wall ratio on performance measures for a south-facing perimeter office space is shown in Figure 4. Its is clearly shown that, increasing window area more than 30%-40% would only increase energy demand while not providing the space with more daylight.

For 40% window-to-wall ratio, the impact of electric lighting control on energy performance was investigated for two control options: (i) passive control and (ii) active on/off automatic control with occupancy sensors. Lighting control reduces significantly the energy required for cooling and lighting (Figure 5).

The impact of shading was evaluated using a roller shade as an example. The properties and control of the roller shade were studied as design parameters. The variation of the daylight availability ratio with shade transmittance indicates that the new daylighting saturation region occurs at about 20% roller shade transmittance for both shading control options. For this value, active automatic shading

control results in 20% more annual daylight availability ratio (60%) compared to passive shading control (40%). This means that people could work for 20% more time in a year without using artificial lighting. Except for energy savings, this translates in possible increase in productivity.

Shading properties and control also have a direct impact on electricity demand for lighting. Assuming active on/off lighting control (based on previous results), annual electric lighting energy demand is reduced by 60% for active automatic shading control (compared to passive lighting control).
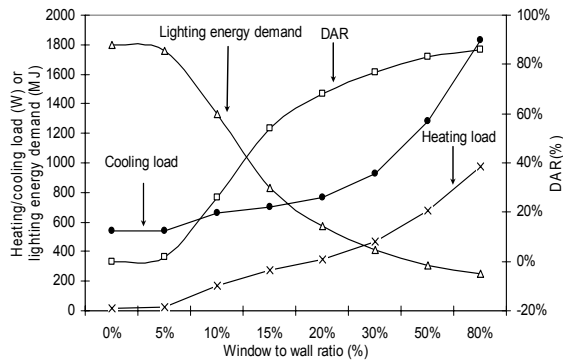

Figure 4: The impact of WWR on performance indices for a south-facing office space in Montreal.
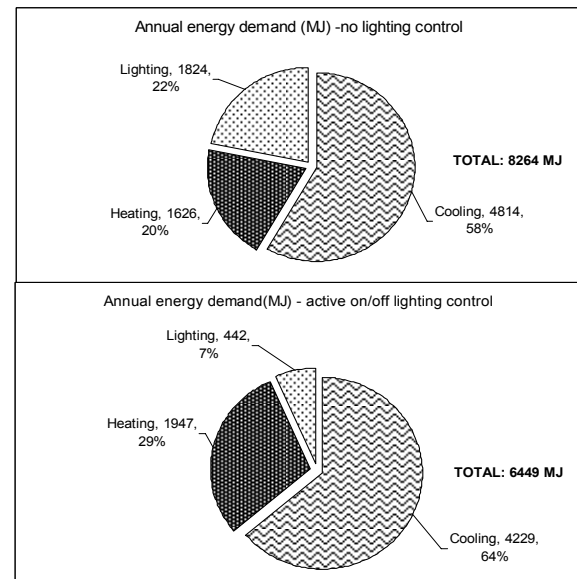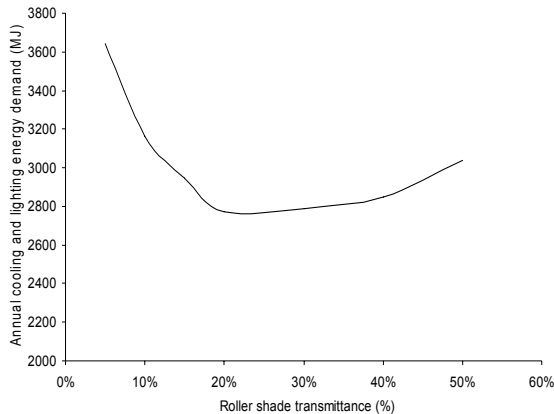

Figure 5: The impact of lighting control on heating. Cooling and lighting demand.

The hourly thermal simulation module runs as a function of shade transmittance and control. The impact of shading control on transmitted solar radiation is modelled with schedule functions of shade transmittance as described above. Internal gains from lights are therefore predicted as a function of roller shade properties for each working hour, taking into account the impact of shading control. Cooling energy demand is plotted as a function of shade transmittance, taking into account active automatic shading and lighting control. The curve that shows the

sum of cooling and lighting energy demand is possibly the most important. Since shading is used for reduction in cooling requirements (except for glare), this is the curve that shows the integrated benefits of daylighting, shading and electric lighting control. This key integrated performance measure, shown in Figure 6, indicates that optimum energy performance is only achieved if daylighting benefits due to reduced electric lighting operation (and the subsequent reduction in cooling requirements) exceed the increase in energy demand due to increased solar gains, which is always affected by shading control. The variation of this index with shading properties helps in investigating if this region exists. Figure 6 shows that, for the considered case, it exists and it occurs for 20% roller shade transmittance. For smaller transmittance values, poor daylighting conditions result in large internal gains due to continuous electric lighting operation during working hours; therefore both cooling and lighting demand increase. For higher transmittance values, daylight availability is adequate but excessive solar gains result in an increase of cooling demand which is higher than the reduction due to reduced internal gains. Active automatic shading and lighting control make it possible for this integrated performance index to reach a minimum for a certain roller shade transmittance value. For warmer climates, the optimum would shift to the left (smaller transmittance values), since cooling energy would be much higher. Moreover, the total energy consumption could be minimized for cooling-dominated climates.


Figure 6: A new performance index as a function of shade transmittance.

The impact of shading and lighting control on the energy performance during a hot summer day is shown in Figure 7 and the combined impact of glazing R-value, lighting control and shading control on peak thermal loads is presented in Figure 8. It is clear that shading control is the most important factor.
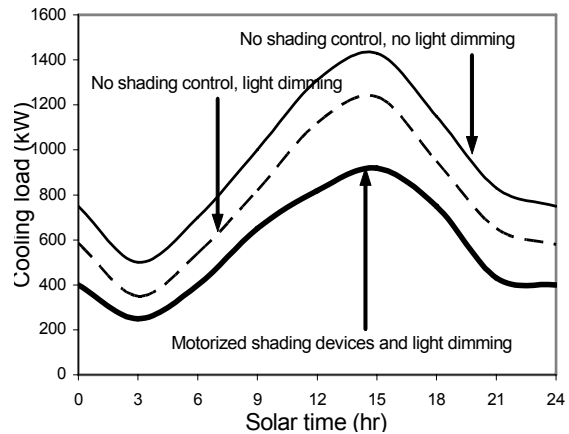
Figure 7: The impact of shading and lighting control on cooling load during a hot day.
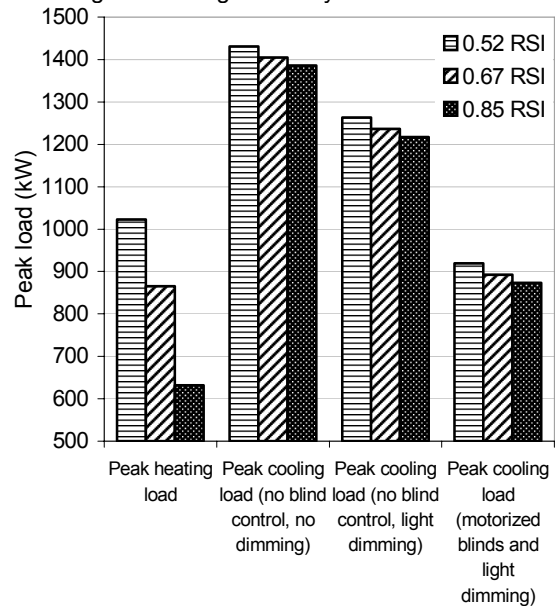

Figure 8: How glazing R-value, light dimming and shade control affect peak thermal loads in a perimeter office space in Montreal.

A general comparison of the integrated daylighting and thermal analysis results (including the shading impact) with the base case (30% window-to-wall ratio) and passive and active electric lighting control is presented in Figure 9. Shading control has the highest impact on cooling energy demand, which is drastically reduced by almost 50% (from 4060 MJ to 2054 MJ) compared to active lighting control without shading. Lighting energy demand is of course mostly affected by lighting control and increases by 38% (from 442 MJ to 720 MJ) if shading is used because of decrease in daylight availability (although shading control takes into account daylight maximization). However, utilization of an exterior shade with 20% transmittance and active automatic control results in reduction in total annual energy demand by 12% (from 6449 MJ to 5674 MJ). This happened because:

(i) cooling is more important than heating for south-facing perimeter spaces;

(ii) the energy benefits of daylighting, with active automatic shading and lighting control, were higher

than the penalty due to increase of solar gains (for 20% shade transmittance) and an optimum balance between controlled solar gains and internal gains can be achieved (Figure 6).

Although a shade transmittance value close to 20% satisfies daylighting and cooling requirements, it is expected that a roller shade with 20% transmittance would create glare problems. A solution to this inconvenience is the separation of window area in two parts. The bottom part should have a lower transmittance than the upper part to protect from glare, but the average should approach 20%. For example, this could be achieved using venetian blinds in the upper part, or a roller shade with variable transmittance based on a three-section façade concept [8].
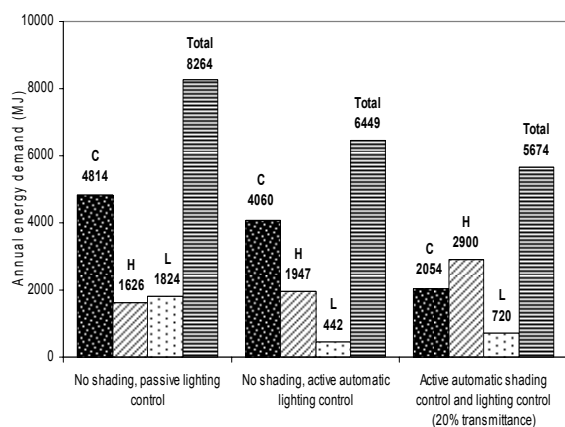
Figure 9: A general comparison of design schemes concerning lighting and shading.

4. CONCLUSION

This paper presented the method and results of a simulation-based integrated thermal and daylighting analysis for perimeter office spaces. The objectives were to (i) to evaluate the impact of façade design alternatives –glazing area and shading properties and control- on the thermal and daylighting peroformance of office buildings at the early design stage and (ii) to provide guidelines on selecting glazing area and shading properties at this preliminary stage.

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. 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. Results showed that, for a south-facing office in Montreal, 30% window-to-wall ratio with on/off lighting control and automatic shading control could reduce lighting demand by 53% and cooling energy demand by more than 50%. At the same time, daylighting can be ensured for the occupants for most of the time using appropriate shading types and control.

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