A tool for integrated thermal and lighting analysis of spaces with controlled Complex Fenestration Systems and artificial lighting

Germán Molina[1], Sergio Vera[2], Waldo Bustamante[3]

[1,2] Department of Construction Engineering and management, School of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile

[3] School of Architecture, Pontificia Universidad Católica de Chile, Santiago, Chile

Abstract

Complex Fenestration Systems (CFS) are those that incorporate a non-specular layer within the glazing assembly, such as a shading device. CFS are often used in buildings for simultaneously enhance thermal and visual comfort and reducing energy consumption. Currently existing tools allow performing efficient lighting and thermal annual simulations of spaces with CFS. However, carrying out a detailed integrated lighting/thermal analysis is a complex task that cannot yet be transferred to industry. A tool for simplifying this process is required. This article presents a methodology for performing simple integrated thermal/lighting analysis of spaces with controlled CFS and artificial lighting during the design stage. Such methodology uses Radiance's *genBSDF* program for characterizing CFS and a new Radiance-based program called *mkSchedule*, which helps integrating the lighting and thermal simulations. This paper demonstrates how the proposed methodology works by performing an integrated annual analysis of an office space with controlled CFS and artificial lighting.

1 Introduction

Complex Fenestration Systems (CFS) have been defined as those that include a non-specular layer within the glazing assembly (Laouadi & Parekh 2007). This definition includes fenestrations attachments that have complex thermal and optical behaviour (ASHRAE 2013) such as all non-specularly transmitting fenestration system components like fabric shades and louvered blinds (McNeil et al. 2013). CFS usually present complicated and strong angular dependency in their optical properties, making them difficult to model in lighting and energy-performance simulation tools. For example, EnergyPlus (Crawley et al. 2001; Crawley et al. 2004) used to model shading devices as perfectly diffusive layers with a single value that represented their optical properties (Winkelmann 2001), which corresponds to a gross assumption that can lead to important errors.

Modeling a CFS within energy-performance or lighting simulation software requires considering the angular dependence of their optical properties. This can be achieved using the concept of Bidirectional Scattering Distribution Functions (BSDF) (Nicodemus, 1970; Nicodemus et al., 1977). BSDF are relations between the incoming Irradiance and the outgoing Radiance. For CFS, they are often expressed in the form of matrices, where each column represents an incoming direction, and each row represents an outgoing direction from the discretized incoming and outgoing semi-hemispheres. (Klems et al. 1995; Klems 1994b; Klems 1994a). The advantage of such functions is that they can represent arbitrarily complex bidirectional functions (no analytical curve or surface has to be fitted to measured or calculated data). However, the semi-hemisphere discretization can lead to errors when very specular shading systems are being modeled (i.e. when one patch is too big to accurately represent a luminance peak on the outgoing radiation). This last drawback is partially solved by using adaptive BSDF representation (in the form of tensor trees instead of matrices) that can vary their resolution to accommodate specular and diffuse sectors (Ward et al. 2012).

Nowadays, Radiance lighting simulation suite (Ward 1994) can model CFS using their BSDFs in both matrix and tensor tree forms (Konstantoglou et al. 2009; Ward et al. 2011). On the other hand, EnergyPlus (Crawley et al. 2004; Crawley et al. 2001) and ESP-r (ESRU, 2013) are nowadays capable of using Bidirectional information to more accurately represent CFS within energy performance simulations (Frontini et al., 2009; LBNL, 2013a). Nevertheless, performing an integrated lighting and thermal analysis of a building design is still not a simple task since these domains interact in many levels (i.e. luminaires generate internal heat gains and also modify the lighting levels in the building) and simulation tools are usually specialized in only one of these domains.

Suing different methodologies, McNeil et al. (2013) and Molina (2014) have evaluated Radiance's genBSDF program as a tool for the assessment of solar and visible BSDF of CFS.. Both studies show that Radiance can be used for the CFS optical characterization during the design stage, allowing a detailed thermal and lighting analysis in established simulation tools.

On the other hand, Molina (2014) improved the methodology presented by Wienold et al. (2011) for carrying out integrated thermal and lighting analysis, with the purpose of making it more flexible and time-efficient. Wienold's methodology consists of three steps: (1) multiple lighting simulations are performed using Daysim (Reinhart 2013); (2) a control algorithm is applied to the results in order to choose artificial lighting power and shading position for each simulation timestep; and (3) the chosen positions and luminaire power are transferred to ESP-r for carrying out detailed energy performance simulations. It is worth noticing that the key of Wienold´s methodology is the use of schedules for coordinating the lighting and thermal simulations. Accordingly, the Molina´s improved methodology simplifies the generation of such schedules using a new Radiance-based program called *mkSchedule,* which utilizes the Three-phase method (Saxena et al. 2010; McNeil & Lee 2013; McNeil 2013) instead of Daysim for simultaneously performing the lighting simulation and implementing controls (steps 1 and 2 of Wienold's methodology). This new methodology separates the control sensors (i.e. those whose measurements will be used control luminaires or CFS) from the workplane sensors (i.e. those that will be analyzed to quantify quality of the light in the space). Working with only the control sensors makes the process of creating schedules faster and more realistic (i.e. control is usually done by installing one or two photosensors on the ceiling, and not many of them in actual the workplane). The schedules are then used for carrying out both detailed energy performance and lighting simulations, and their results can be analyzed simultaneously in order to quantify the thermal and visual comfort and the whole-building energy consumption.

This paper aims to integrate the use of Radiance's *genBSDF* and the new program, *mkSchedule,* into a workflow that allows performing integrated thermal and lighting analysis of spaces with controlled artificial lighting and CFS during the design stage. The methodology is presented in Figure 1. The process starts by designing the building and its surroundings. Second, the designer may choose weather to incorporate an existing CFS (i.e. from WINDOW) or to design a completely new CFS. In the latter case, the BSDF of the custom CFS are assessed using Radiance's *genBSDF.* Third, the designer must choose locations for photosensors that will control the luminaires and CFS. . For those sensors, ray-tracing calculation of the matrices required for implementing the Three-phase method (McNeil 2013; McNeil & Lee 2013;

Saxena et al. 2010) is done, in order to allow performing fast lighting simulation. Fourth, *mkSchedule* is used to generate schedules that contain the position of the CFS and the artificial lighting power for each timestep. Fifth, energy performance and lighting simulation tools are employed for performing a detailed schedule-driven simulation. Finally, the results must be analysed holistically in order to consider both the lighting and thermal behaviour of the building.

The following sections show how this workflow works by implementing it for a simple case study.

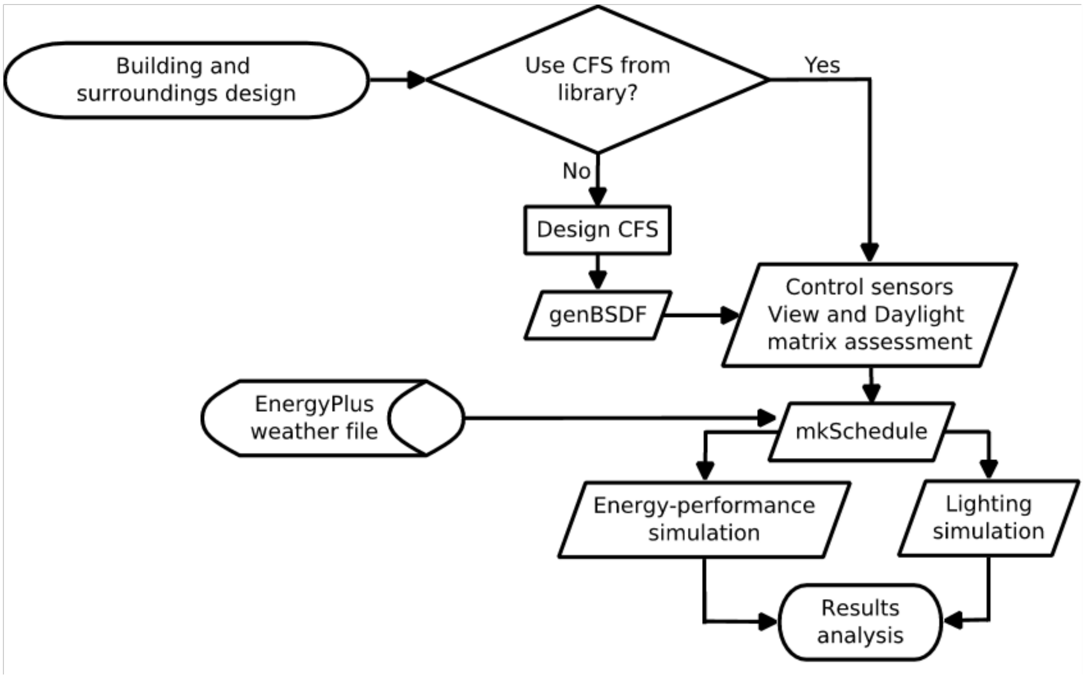

Figure 1: Proposed workflow for integrated thermal and lighting analysis and design

2 Building, surroundings and window openings design

The case study corresponds to a 5 m by 8 m office space. Two walls are adiabatic representing interior walls and considering this office space could be part of a building's floor. The other two walls are in contact with the outdoor environment and two sets of window openingsa are placed on them. The first set consists on one large south-facing fenestration and the second set consists of five small windows facing east. The office is located in Boulder, Colorado (USA). As first step of the workflow, the office was designed in SketchUp as shown in Figure 2, and then exported in Radiance format. This figure also shows the surrounding, which was imported to SketchUp from Google Earth. The weather file to be used in the simulations corresponds to an EnergyPlus Weather File of the same city.

It is important to notice that, even though CFS will be installed in the windows, they have not yet been added in the design. This is because using BSDF allows treating them as black boxes, and no detailed geometry has to be included in the lighting or thermal model.

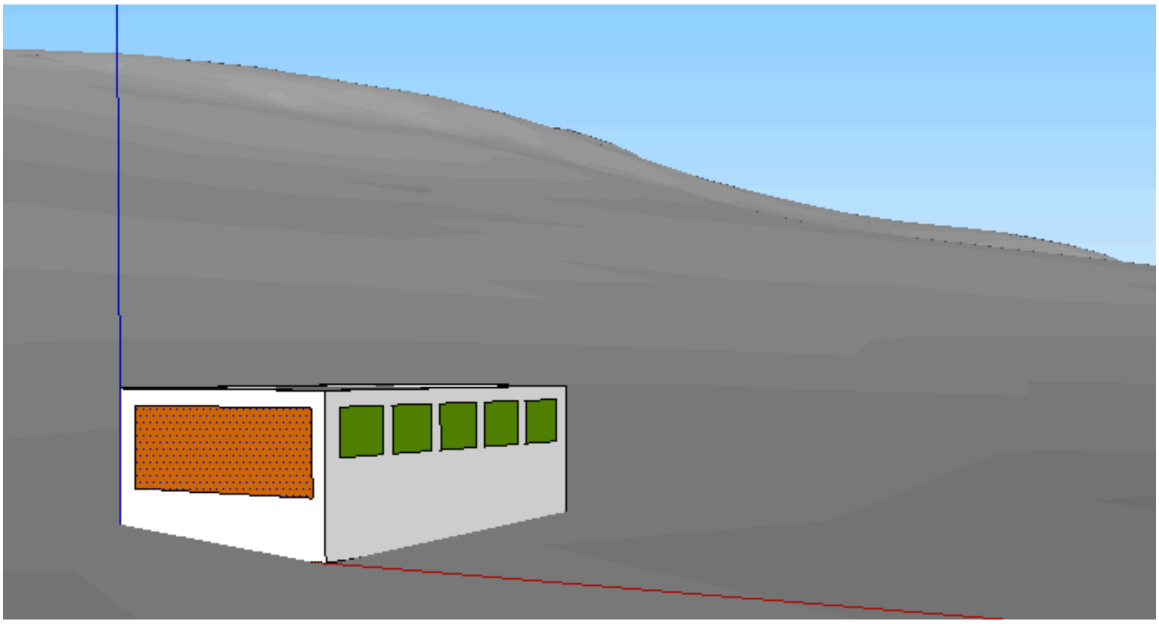

Figure 2: Space to be simulated and surroundings imported from Google Earth.

3 Fenestration system design

At this step the designer may choose to use known CFS or to design them. In this latter case, two custom shading systems were used. One of them corresponds to a set of venetian blinds, installed on the large south-facing window, that were generated using Radiance's *genblinds* program. The other corresponds to a set of horizontal slats, as shown in Figure 3, installed on five small east-facing windows. This system was designed in SketchUp and exported to Radiance. While the venetian blinds are movable and allow choosing from six different angles (0°, 15°, 30°, 45°, 60° and 75°), the other shading device is fixed.

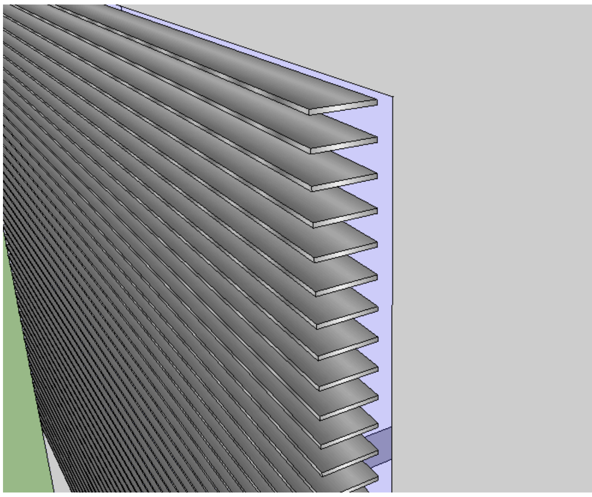

Figure 3: East-shading system designed in SketchUp.

The materials of both shading devices are the same and correspond to a reflective metal (80% solar and visible reflectance) with 90% specularity.

4 Fenestration system properties assessment

Since custom CFS are used, assessment of their BSDF is needed. There are several options for doing this, such as performing laboratory measurements, developing analytical models and emulating the laboratory experiment in a virtual environment using ray-tracing techniques (Andersen & de Boer, 2006). However, since the materials used in these CFS are specular and the shading systems to be evaluated have not been built, ray-tracing techniques are the only option available for this case as often happens at the design stage.

Ray-tracing techniques have been used for the assessment of bidirectional properties in various studies, (Rubin et al. 2007; Konstantoglou et al. 2009; McNeil & Lee 2013). In this study, Radiance's program *genBSDF* will be used for assessing both the visible and the solar bidirectional properties for lighting (Radiance) and energy performance (EnergyPlus) simulations, respectively.

The BSDFs were obtained in the Tensor-tree form, which would allow performing different analysis (i.e. renders or detailed ray-tracing analysis) and then efficiently transformed to the matrix form to perform the annual simulations. This transformation was made using Radiance's *bsdf2klems* program.

After generating the solar BSDF for each shading position, they were imported to WINDOW 7.2 (LBNL, 2013b) to be lately exported into an EnergyPlus readable format.

5 Schedule creation

Since CFS are often installed to provide enhanced visual and thermal comfort as well as to reduce cooling energy consumption, performing integrated lighting and thermal analysis of spaces with CFS can be considered even more important than in simple cases. Accordingly, this step is probably the most important part of the workflow and will be more deeply explained than others.

There are several options for carrying out integrated lighting/thermal analysis (Tzempelikos & Athienitis 2007; Petersen & Svendsen 2010; Janak 1997; Guglielmetti et al. 2011). In Molina (2014), the methodology used by Wienold et al. (2011) was improved. Wienold's methodology required performing multiple lighting simulations using Daysim, implementing a control algorithm over the results of the previous step for generating a schedule, and a posterior schedule-driven ESP-r energy-performance simulation. This approach is time-consuming as the Daylight Coefficients (Tregenza & Waters 1983) used by Daysim need to be recalculated when the building envelope is modified. Therefore, the use of the Three-phase method (Saxena et al. 2010; McNeil 2013; Ward et al. 2011) is recommended. By implementing such method, simultaneous lighting simulation and control implementation can be performed. The Three-phase method involves time-consuming ray-tracing calculations in order to assess two matrices, Daylight (D)and View (V) matrices. While D represents the light transport from the sky to the exterior side of the windows D corresponds to the light transmission from the interior side of the windows to the scene. Then, the lighting simulation is performed by calculating the product of these two matrices, the visible BSDF of the CFS installed in the window, and a vector that represents the luminous distribution of the sky.

Description of a new program

MkSchedule is a new program developed by Molina (2014) which is based on Radiances's *dctimestep* and *gendaymtx* programs. They allow implementing the Three-phase method and creating the Perez's sky (Perez et al. 1993; Perez et al. 1990) that are required for the simulations. Also, since the use of EnergyPlus weather files was desired another important part of *mkSchedule* was extracted from Daysim's *epw2wea* program. This part reads and selects information from the weather files which is needed for the simulations. *mkSchedule* was developed with the intention of simplifying the generation of schedules used by Wienold et al. (2011), allowing easier integration of the lighting and thermal simulations.

mkSchedule receives as input all the matrices required for Three-phase method calculations, the contributions of the luminaires over the sensors in matrix form (i.e. standard *rcontrib* or *rtrace* Radiance's programs output) and a control algorithm written in Lua scripting language. The output is a schedule file with sensor illuminance values, power fraction of the luminaires, and the shading position represented as an integer.

One of the key features of *mkSchedule* is its flexibility to modify and allow different control algorithms easily while being fast. This is achieved by defining the control algorithm as an argument for the main program, and by allowing the user to program it in Lua, a scripting language much simpler than the main program's C. From the control scripts, the user can call predefined functions in order to retrieve relevant information for making decisions and use it as trigger. For example, luminaire power and shading position can be controlled according to sun position (i.e. azimuth, zenith and altitude), exterior dry-bulb temperature, irradiance over a surface calculated according to Perez et al. (1990, 1993), and as shown in (Duffie & Beckman 1996), illuminance over a sensor, previous luminaire power and shading position, or any information that can be derived from the lighting simulation and/or the EnergyPlus weather file .

Generating the schedule

For this case study, two sets of luminaires were installed as shown in Figure 4, and two control sensors were located in the space to control each of them. It should be noticed that a more realistic approach would be to place the sensors in the ceiling, and correlating their measurements with the workplane illuminance as explained in (Tzempelikos 2012). However, in this case, the sensors were located just under the central luminaire of each set pointing to the ceiling in order to simplify the example.

The Lua control script consists on three steps: (1) position the south-facing venetian blind according to the solar irradiance over the south-facing window; (2) recalculate the illuminance values on the interior because the daylighting levels of the space have been modified due to the new position of the blinds; and (3) dim the luminaire power to achieve the desired illuminance on the sensors.

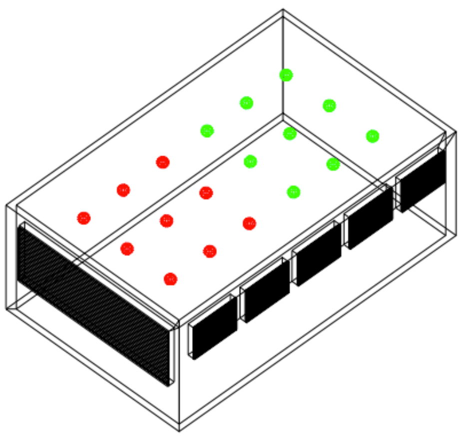

Figure 4: Space showing two luminaire sets represented by red and green dots.

The position of the venetian blinds will be chosen according to the irradiance on the south-facing façade, gradually closing them when this value increases. The simulation will emulate a pyranometer installed vertically on the façade that automatically controls the positions the venetian blind. Two control algorithms with different sensitivity were evaluated for positioning the venetian blinds. These algorithms are named 700 W/m^2 and 100 W/m^2, being these the values that were arbitrarily chosen to close (i.e. position at 75°) the venetian blinds. The positions of the blinds according to south-facing irradiance can be seen in Figure 5. This figure shows that blind are closed in one step when irradiance is over 100 W/m^2, while blinds are closed gradually for the control algorithm with a threshold of 700 W/m^2, always allowing the same or less solar heat gains and daylight.

Figure 6 shows the position of the venetian blind during 48 hours of the year according to the generated schedule. As expected, the 100 W/m^2 control algorithm causes that the venetian blind remains closed almost all the time during daytime, while the 700 W/m^2 algorithm allows various positions. Also, during the night, both algorithms keep the blinds fully open.

The impact of the two control algorithms on the illuminance for the first 48 hours of the simulation can be seen in Figure 7. As expected, the nighttime illuminance of both algorithms is the same (only artificial lighting), while the 100 W/m^2 algorithm allows less daylight during daytime than that for the 700 W/m^2 control algorithm.

The fact that the results agree to what was expected proves that *mkSchedule* is working properly. Also, it is expected that similar results will be shown in the detailed thermal and lighting analysis, meaning that the 100 W/m^2 control algorithm is expected to provide less daylight and solar heat gains than the 700 W/m^2 control algorithm during daytime.

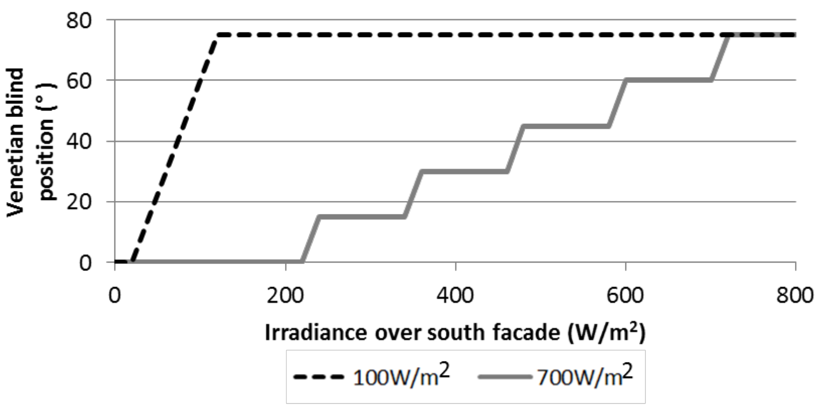

Figure 5: Position of the venetian blind according to the irradiance in the south facade for each algorithm for both venetian blind control algorithms

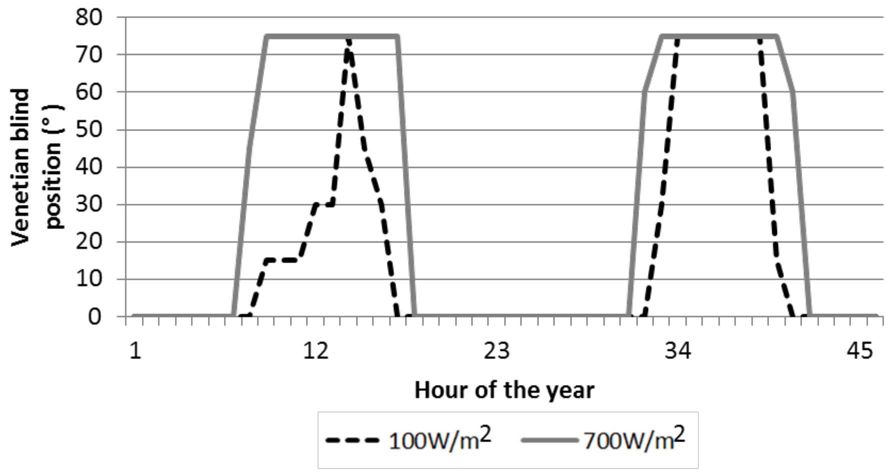

Figure 6: South-facing venetian blind position during two days of the year for both venetian blind control algorithms

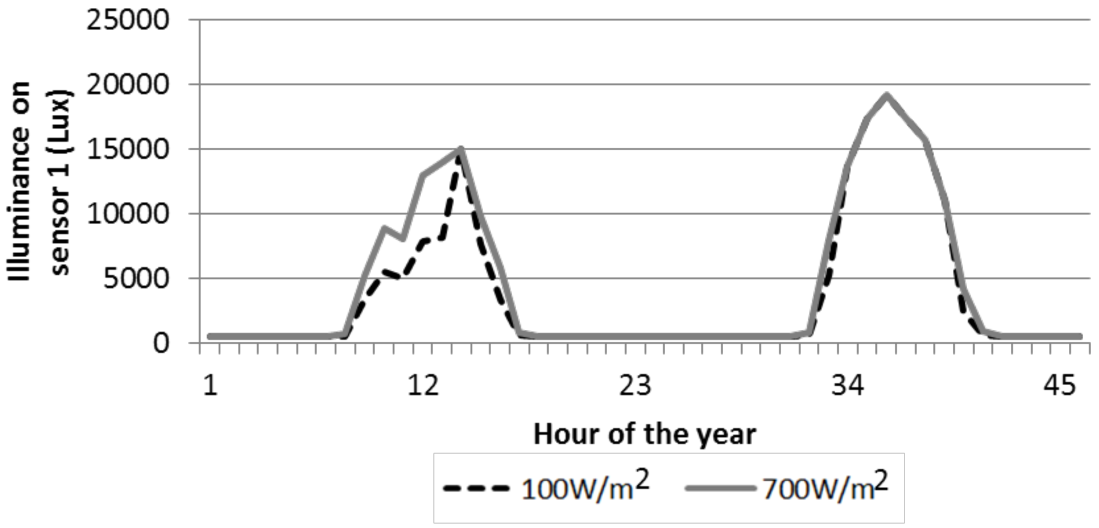

Figure 7: Illuminance in sensor 1 for both venetian blind control algorithms during 48 hours of the year

6 Lighting simulation

The lighting simulation was carried out using a routine that, at each timestep, implemented the Three-phase method for each window and then summed them together along with the luminaire contribution. For this analysis, 375 sensors were placed in a horizontal workplane located at 0.8 m above the floor.

The results of the calculated illuminance are shown in Figure 8 in a temporal map. On temporal maps, the x-axis corresponds to the day of the year, and the y-axis corresponds to the hour of the day. It can be seen, for example, that the days are longer during the summer (central months of the year). The colors in the temporal map were assigned using the Lightsolve´s goal-based approach (Andersen, Kleindienst, Yi, J., et al. 2008; Andersen, Kleindienst, Yi, Lee, et al. 2008). This format, explained in (Andersen et al. 2011), shows how closely the different sections in the workplane meet the goals of illuminance. That is, on each timestep, each sensor is evaluated to check the percentage of the workplane that is getting more illuminance than the desired, less illuminance than the desired, and the percentage that is within the desired range. Then, this information is transformed into a color according to the scale present in the same figure. In this case, the desired range was between 500 Lx and 3000 Lx, and any values over this range will be considered excessive, and any value below this range will be consider insufficient.

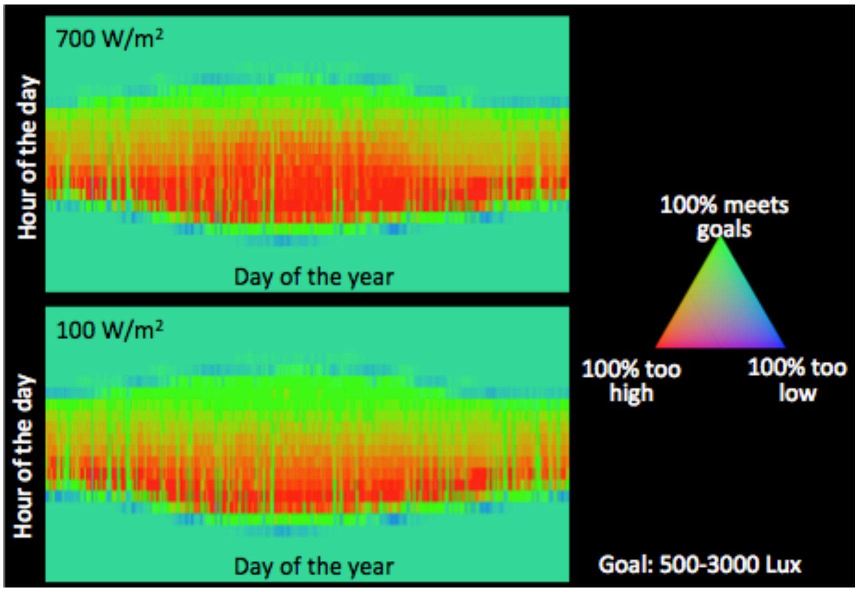

Figure 8: Results of the lighting simulation in Lightsolve format.

The results show that both the 700 W/m^2 and 100 W/m^2 algorithms allow excessive daylight along the year, mainly in the morning. This is caused by the 5 small east-facing windows, which allow morning daylighting, and the large fenestration surface in the south-facing façade. As expected, the 100 W/m^2 control algorithm allows less illuminance than the 700 W/m^2 control algorithm during daytime and the same illuminance during nighttime, which is when only artificial lighting is available.

7 Energy performance simulation

The energy performance simulation was carried in EnergyPlus. Both the luminaires and the CFS were controlled using the schedule generated earlier, which was also used for performing the lighting simulation.

The results of the calculated solar heat gains are shown in a temporal map in Figure 9. This figure shows that, as expected, the solar heat gains through the south-facing window for both control algorithms. Since the two algorithms differ on their sensitivity to solar irradiance, it is clear that the 700 W/m^2 algorithm allows higher solar heat gains than the 100 W/m^2, especially during summer.

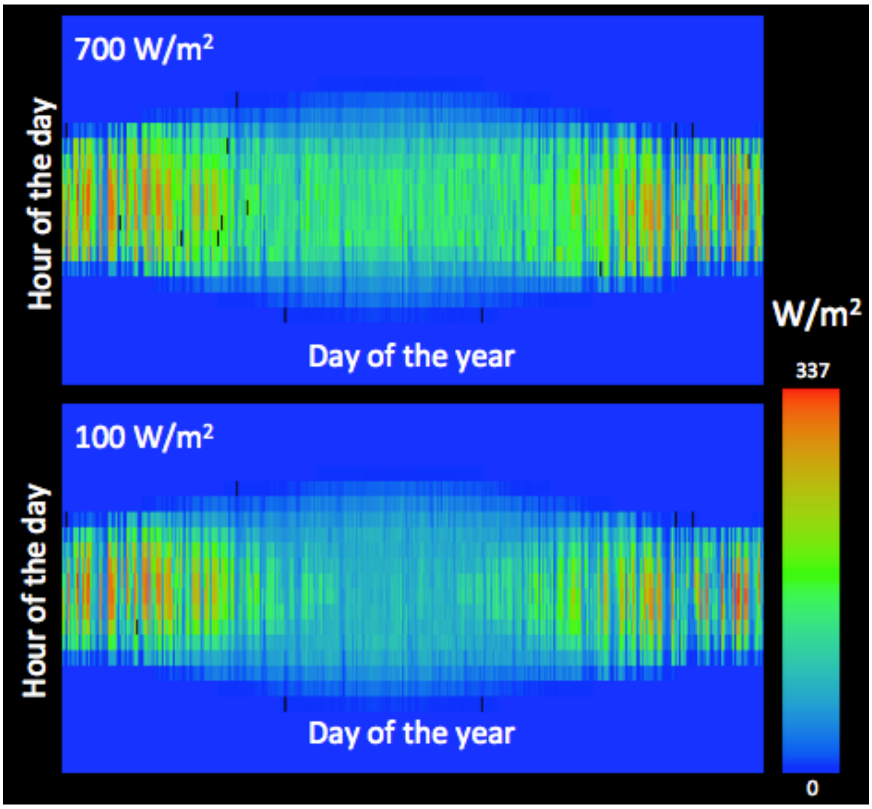

Figure 9: Transmitted solar energy through the South-facing window, reported from EnergyPlus.

For performing the energy consumption analysis, the space was provided with an ideal-load air HVAC system. Monthly reports of heating, cooling and lighting energy consumption were generated using EnergyPlus. This analysis assures reliable results by using EnergyPlus to calculate the heating and cooling energy consumption, and by reporting the artificial lighting energy consumption using the lighting information available from the schedule generated using Radiance.

The difference in energy consumption between both algorithms is plotted in Figure 10. It shows that the 100 W/m^2 algorithm reduces the cooling energy consumption (54 kWh in September and 115 kWh in July), and increases both the lighting (5 kWh in December) and heating (3 kWh in December) energy consumption when compared to the 700 W/m^2. This behaviour was expected because of the reduction of the solar heat gains and daylight achieved by the 100 W/m^2. During the whole year, the energy consumption increases in 15 kWh and 12 kWh in terms of Lighting and Heating and decreases in 985 kWh in Cooling. The total energy savings correspond to 958 kWh, which is the 7% of the original (700 W/m^2) energy consumption. In addition to this, the results of the lighting simulation shown in Figure 8 suggest that the 100 W/m^2 algorithm not only saves energy, but also might provide a more visually confortable environment.

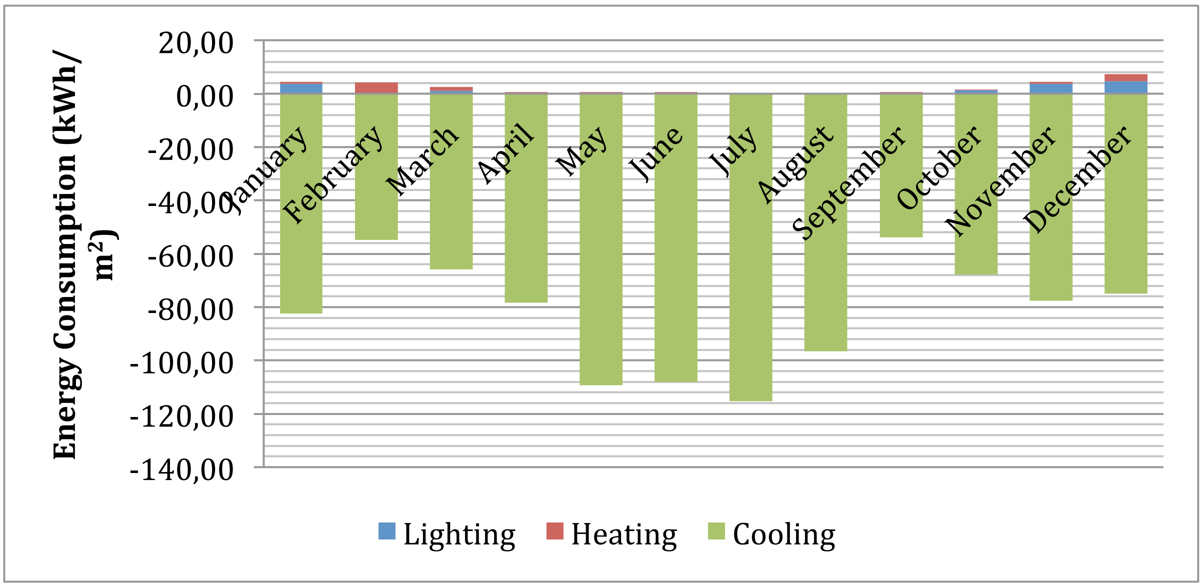

Figure 10: Difference in monthly energy consumption of the space between the 100W/m^2 and the 700 W/m^2 algorithms

8 Conclusions and future work

The aim of this paper is to introduce a new methodology for performing integrated thermal and lighting analysis of spaces with controlled CFS and artificial lighting that can be applied during the design stage of buildings. This process allows designing the building itself, the CFS, the artificial lighting and even the control algorithms to be used for controlling the CFS and luminaires. Radiance's *genBSDF* program allows assessing the solar-optical properties that can be used within Radiance and EnergyPlus for performing detailed lighting and energy performance simulations, respectively. A new program called *mkSchedule* allows generating schedules of luminaries power density and CFS operation. This information is used to couple the lighting and thermal domains.

The new methodology was tested using a simplified office case study which is located in Boulder, Colorado (USA). The results agree well accordingly to the control strategies defined for the CFS and luminaries.

In summary, the presented methodology allows designing the building, CFS, luminaires and control algorithms, and evaluating the design in a holistic lighting/thermal simulation.

9 Acknowledgements

This work was funded by the National Commission for Scientific and Technological Research of Chile (CONICYT) under the research grant FONDECYT 1111001. The authors also gratefully acknowledge the support provided by CEDEUS, CONICYT/FONDAP 15110020. Some aspects of this work were developed during the stay of Germán Molina at Concordia University (Montreal, Canada), which was funded by the Canada-Chile Leadership Exchange Scholarship.

10 References

Andersen, M., Kleindienst, S., Yi, L., Lee, J., et al., 2008. 462 : Informing daylighting design with the Lightsolve approach : why and how. In *PLEA - 25th Conference on passive and Low Energy Architecture*.

Andersen, M., Kleindienst, S., Yi, L., J., L., et al., 2008. An intuitive daylighting performance analysis and optimization approach. *Building Research & Information*, 36(6), pp.593–607.

Andersen, M. & de Boer, J., 2006. Goniophotometry and assessment of bidirectional photometric properties of complex fenestration systems. *Energy and Buildings*, 38(7), pp.836–848.

Andersen, M., Gagne, J.M.L. & Kleindienst, S., 2011. Informing well - balanced daylight design using Lightsolve. In *CISBAT11: CleanTech for Sustainable Buildings - from Nano to Urban scaleLausanne, S*. Lausanne, Switzerland.

ASHRAE, 2013. *ASHRAE Handbook-fundamentals*, Atlanta, USA: American Society of Heating Refrigerating and Air Conditioning Inc.

Crawley, D.B. et al., 2001. EnergyPlus : creating a new-generation building energy simulation program. *Energy and Buildings*, 33, pp.319–331.

Crawley, D.B. et al., 2004. EnergyPlus : New , capable and linked. In *Proceedings of the SimBuild*. Boulder, CO.

Duffie, J. & Beckman, W., 1996. *Solar Engineering of Thermal Processes* Third., Hoboken, New Jersey, USA: John Wiley & Sons.

Energy Systems Research Unit, 2013. ESP-r website. Available at: http://www.esru.strath.ac.uk/Programs/ESP-r.htm.

Frontini, F. et al., 2009. Implementation and application of a new bi-directional solar modelling method for complex facades within the ESP-r building simulation program. In *Eleventh international IBPSA Conference*. Glasgow, Scotland, pp. 936–943.

Guglielmetti, R., Macumber, D. & Long, N., 2011. OpenStudio: An Open Source Integrated Analysis Platform. In *12th International Conference of International Building Performance Simulation Association*. Sydney, Australia, pp. 1–9.

Janak, M., 1997. Coupling building energy and lighting simulation. In *5th International IPBSA Conference*. Prague, Czech Republic.

Klems, J.H., 1994a. A new method for predicting the solar heat gain of complex fenestration systems I. Overview and Derivation of the Matrix Layer Calculation. *ASHRAE Transactions*, 100(1), pp.1065–1072.

Klems, J.H., 1994b. A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems II. Detailed Desctription of the Matrix Layer Calculation. *ASHRAE Transactions*, 100(1), pp.1073–1086.

Klems, J.H., Warner, J.L. & Kelley, G.O., 1995. *ASHRAE Solar Heat Gain Project 548-RP final feport: A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems*, Springfield, VA, USA.

Konstantoglou, M., Jonsson, J. & Lee, E., 2009. Simulating Complex Window Systems using BSDF Data. In *26th Conference on Passive and Low Energy Architecture*.

Laouadi, A. & Parekh, A., 2007. Optical models of complex fenestration systems. *Lighting Research and Technology*, 39(2), pp.123–145.

Lawrence Berkeley National Laboratory, 2013a. EnergyPlus Engineering Reference The Reference to EnergyPlus Calculations.

Lawrence Berkeley National Laboratory, 2013b. WINDOW website.

McNeil, A. et al., 2013. A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems. *Solar Energy*, 98, pp.404–414.

McNeil, A., 2013. The Three-Phase Method for Simulating Complex Fenestration with Radiance. , (March), pp.1–33. Available at: http://www.radiance-online.org/learning/tutorials/Tutorial-ThreePhaseMethod.pdf.

McNeil, A. & Lee, E.S., 2013. A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems. *Journal of Building Performance Simulation*, 6(1), pp.24–37.

Molina, G., 2014. *Integrated thermal and lighting analysis of spaces with controled complex fenestration systems and artificial lighting during the design stage*. Pontificia Universidad Católica de Chile.

Nicodemus, F.E. et al., 1977. Geometrical considerations and nomenclature for reflectance. , (October).

Nicodemus, F.E., 1970. Reflectance Nomenclature and Directional Reflectance and Emissivity. *Appled Optics*, 9(6), pp.1474–1475.

Perez, R. et al., 1990. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar energy*, 44(5), pp.271–289.

Perez, R., Seals, R. & Michalsky, J., 1993. All-weather model for sky luminance distribution—Preliminary configuration and validation. *Solar Energy*, 50(3), pp.235–245.

Petersen, S. & Svendsen, S., 2010. Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*, 42(7), pp.1113–1119.

Reinhart, C.F., 2013. http://daysim.ning.com/.

Rubin, M., Jonsson, J. & Kohler, C., 2007. Bidirectional Optical Properties of Slat Shading: Comparison Between Raytracing and Radiosity Methods.

Saxena, M., Ward, G. & Perry, T., 2010. Dynamic Radiance–Predicting annual daylighting with variable fenestration optics using BSDFs. *SimBuild*, pp.402–409.

Tregenza, P.R. & Waters, I.M., 1983. Daylight coefficients. *Lighting Research and Technology*, 15(2), pp.65–71.

Tzempelikos, A., 2012. Development and Implementation of Lighting and Shading Control Algorithms in an Airport Building. *Journal of architectural engineering*, (18), pp.242–250.

Tzempelikos, A. & Athienitis, A.K., 2007. The impact of shading design and control on building cooling and lighting demand. *Solar Energy*, 81(3), pp.369–382.

Ward, G., 1994. The RADIANCE lighting simulation and rendering system. *Proceedings of the 21st annual conference on Computer graphics and interactive techniques - SIGGRAPH '94*, pp.459–472.

Ward, G., Kurt, M. & Bonneel, N., 2012. *A Practical Framework for Sharing and Rendering Real-World Bidirectional Scattering Distribution Functions*,

Ward, G., Mistrick, R. & Lee, E.S., 2011. Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within Radiance. *Leukos*, 7(4).

Wienold, J. et al., 2011. Climate based simulation of different shading device systems for comfort and energy demand. In *12th Conference of International Building Performance Simulation Association*. Sydney, pp. 14–16.

Wienold, J., 2009. Dynamic Daylight Glare Evaluation. In *Eleventh international IBPSA Conference*. pp. 944–951.

Winkelmann, F.C., 2001. Modeling windows in EnergyPlus. In *7th International IBPSA Conference*. Rio de Janeiro, Brazil, pp. 457–464.