UNIVERSIDADE FEDERAL DO PARANÁ

LETÍCIA KARINE SEKI UEHARA

POTENCIAL DA JANELA FOTOVOLTAICA PARA EDIFÍCIOS DE ESCRITÓRIO COM MÚLTIPLOS PAVIMENTOS: AVALIAÇÃO DA ILUMINAÇÃO NATURAL EM TERMOS DE ILUMINÂNCIA E OFUSCAMENTO

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Orientador: Prof. Dr. Aloísio Leoni Schmid

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ENGENHARIA DE CONSTRUÇÃO CIVIL da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **LETÍCIA KARINE SEKI UEHARA** intitulada: **POTENCIAL DA JANELA FOTOVOLTAICA PARA EDIFÍCIOS DE ESCRITÓRIO COM MÚLTIPLOS PAVIMENTOS: AVALIAÇÃO DA ILUMINAÇÃO NATURAL EM TERMOS DE ILUMINÂNCIA E OFUSCAMENTO**, após terem inquirido a aluna e realizado a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

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Curitiba, 28 de Junho de 2018.

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To my parents for the opportunities
and hardworking people examples.
To my brother for the incentive and
for believing in my potential.
To Rennan for the support and
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RESUMO

O objetivo desta pesquisa é avaliar o potencial de diferentes tipos de janela fotovoltaica - duas convencionais: com células de silício policristalino e filme fino transparente, e uma não convencional: com células fotovoltaicas orgânicas (OPV) - para edifícios de escritório com múltiplos pavimentos, com salas abertas e plantas profundas em termos de iluminação natural e ofuscamento. Para isto, dividiu-se esta pesquisa em três artigos que se complementam. O primeiro artigo avalia as janelas fotovoltaicas convencionais (policristalina e de filme fino) e as compara com uma janela com vidro simples transparente. Utilizou-se como método para o artigo 1, a simulação computacional no sistema Mestre para analisar se a janela fotovoltaica pode fornecer uma distribuição de luz mais uniforme para uma sala de escritório, garantindo tanto uma maior iluminância no plano de trabalho em uma mesa situada no fundo da sala, quanto um menor efeito do ofuscamento para um trabalhador com vista direta para a janela. Os resultados mostram que, em comparação com a janela de ganho direto (com vidro simples transparente), as janelas fotovoltaicas trabalham com um nível de iluminância 55% menor com uma pequena queda de disponibilidade de luz do dia (apenas 4,7 a 5,7%), mas permite uma queda no DGI de 5 a 7 vezes maior (23,3 a 30,3%). O cálculo do ano inteiro da iluminância do plano de trabalho, os resultados contínuos da Autonomia da Luz do dia (cDA) e do Índice de Luz do Dia (DGI) mostram a superioridade da PV de filme fino com iluminação suplementar. O segundo e o terceiro artigos analisaram um mesmo modelo de escritório genérico e avaliaram um tipo de janela fotovoltaica não convencional, com OPV, e a compararam com uma janela com vidro comum e outra com película solar aplicada no vidro. O segundo artigo comparou estes materiais sob condições de céu real (claro e encoberto) por meio de um experimento com um modelo em escala reduzida, nesta etapa levantou-se dados para posterior inserção no sistema de simulação computacional Radiance. Os resultados obtidos com a medição do modelo reduzido foram utilizados como parâmetros para validar os resultados da simulação computacional (do terceiro artigo) e comprovou-se semelhança entre eles. Desta forma, pode-se avaliar por meio das três pesquisas, o potencial das janelas fotovoltaicas convencionais, policristalina e de filme fino, que são tecnologias mais consolidadas no mercado, e da janela não convencional, com o OPV. Apesar desta última ser uma tecnologia emergente e ainda se encontrar em um estado inicial de pesquisa na busca de células mais eficientes, ainda mostra-se interessante devido às características especiais como: baixo custo de fabricação, caráter escalonável, processo de fabricação simples, baixo consumo de material, sensibilidade a baixos níveis de iluminação e fácil aplicação em grandes áreas.

Palavras-chave: Janela fotovoltaica 1. Simulação computacional 2. Modelo em escala reduzida 3.

ABSTRACT

The goal of this research is to evaluate the potential of different types of photovoltaic windows - two conventional: with polycrystalline silicon cells and transparent thin film, and one unconventional: with organic photovoltaic cells (OPV) - for multi-storey office buildings with open and deep plans in terms of daylighting and glare. Therefore, this research was divided into three articles that complement each other. The first article evaluates conventional photovoltaic (polycrystalline and thin film) windows and compares them with a window with single transparent glass. The method used for the first article is computer simulation based on Mestre system to analyze whether the photovoltaic window can provide a more uniform light distribution for an office room, ensuring with both a higher work plane illuminance on a desk placed deeper into the room, and a smaller glare effect to a worker with direct view to the window. The results show that compared to a direct gain window, a PV window works on a 55% lower illuminance level with a small drop of daylight availability (only 4.7 to 5.7%) but allows a 5 to 7 times bigger (23.3 to 30.3%) drop in DGI. Whole-year calculation of work plane illuminance, continuous Daylight Autonomy (cDA) and Daylight Glare Index (DGI) results show the superiority thin-film PV with supplementary lighting. The second and third articles analyzed the same generic office model and evaluated one type of unconventional photovoltaic window with OPV and compared it with a window with a single transparent glass and another with solar protection film applied to the glass. The second article compared these materials under real sky conditions (clear and overcast) by means of an experiment with a scale model, at this stage data were raised for later insertion in the Radiance system for daylighting simulation. The results obtained with the reduced model were used as parameters to validate the computer simulation results of the third article, and they were found to be almost similar. In this way, the potential of conventional polycrystalline and thin film photovoltaic windows, which are more consolidated technologies in the market, was demonstrated. The potential of the less conventional window with OPV was demonstrated as well. Last type, which despite being an emerging technology and still in an initial state of research has further interest due to the special features such as low manufacturing cost, easy scalability, simple manufacturing process, low material consumption, sensitivity to low lighting levels and easy application in large areas.

Keywords: Photovoltaic window 1. Computer simulation 2. Scale model 3.

FIGURE LIST

LITERATURE REVIEW

ABBREVIATION LIST

AEC	- Architecture, Engineering and Construction
a-Si	- amorphous silicon
BIPV	- Building Integrated Photovoltaics
cDA	- continuous Daylight Autonomy
CIE	- Comission Internationale de l’Eclairage
c-SI	- crystalline silicon
DA	- Daylight Availability
DF	- Daylight Factor
DGI	- Daylight Glare Index
DiNE	- Laboratory of NanoStructured Devices
DSSC	- dye-sensitized solar cells
HDR	- High Dynamic Range
IDS	- Innovative Daylighting Systems
LAC	- Laboratory of Built Environment
LCP	- Laser Cut Panels
MDF	- Medium Density Fiberboard
NREL	- National Renewable Energy Laboratory
OPV	- Organic Photovoltaic
PV	- Photovoltaic
PVW	- Photovoltaic Window

SUMMARY

Chapter 1 PRESENTATION

This research aims to evaluate the application potential of three types of photovoltaic window - PVW (with polycrystalline cells, thin film and with organic cells – OPV) in deep open plan multi-storey office buildings, to verify their contribution related to indoor daylighting quality. Therefore, this thesis was divided into eight chapters. The first one presents this thesis structure.

Chapter 2 contains the general introduction, and brings forward the daylighting importance, the benefits and drawbacks of side windows and the reasons to apply photovoltaic technology in multi-storey office buildings facades. In the end, present the formulation of the research problem. Chapter 3 presents a literature review with some meaningful concepts for understanding the studied subject. Chapter 4 justifies the choice of the methods used and presents some peculiarities of the practice of the methods.

This thesis is presented as a collection of papers. Chapters 5, 6 and 7 correspond to the papers. Titles and abstracts in Portuguese are at the beginning of each chapter.

Chapter 5 contains just the abstract and the website related to the first paper, entitled “Lighting performance of multifunctional PV windows: A numeric simulation to explain illuminance distribution and glare control in offices”, that has already been published in 2017 by Energy and Buildings journal. This paper investigates the performance of two types of semitransparent PV windows, polycrystalline and thin film, and compares them with a single glazing window. Computer simulation based on Mestre system was used to analyze whether the photovoltaic window can provide a more uniform light distribution for an office room, ensuring with both a higher work plane illuminance on a desk placed deeper into the room, and a smaller glare effect to a worker with direct view to the window. As simulation model geometry was considered a generic deep plan office room located in Curitiba (in the southern Brazil) literally lit by one window on the north façade. First a static simulation was performed in order to qualitatively verify the consistency of the algorithms and model geometry. Then, a dynamic simulation was performed with a whole year calculation for illuminance over the work plane, continuous daylight autonomy (cDA) which measures the time that a given point in space is daylit considering the fraction of a specified illumination level and a glare index (DGI).

Second and third papers investigate another type of material for PV windows, OPV, and compare it with two other materials types: single glass and single glass with solar protection film. These papers intend to evaluate horizontal work plane illuminance related to room depth and glare control, not including thermal gains and the amount of energy produced by the photovoltaic window.

Chapter 6 presents the second paper, entitled “Evaluation of the daylighting potential of OPV windows for deep-plan rooms”, that has already been published in 2019 by PARC journal. This research evaluates OPV window potential with a reduced scale model experiment under real sky conditions (overcast and clear) which was carried out in the Exact Sciences Building of UFPR (Federal University of Paraná) in Curitiba-PR. Evaluation was made in a generic office room scale model, illuminated by a side window, which corresponds to the North façade. The room depth is approximately twice the width, what makes it possible to evaluate the daylighting distribution throughout the room depth.

The third paper is contained in Chapter 7, entitled “Daylighting evaluation in deep plan office buildings with OPV windows through simulation on Radiance”, that has already been published in 2022 by Acta Scientiarum Technology journal. This research uses the same physical scale model (second paper) conditions and parameters as computer simulation input data in the Radiance system. Thereby, the experiment and simulation results were compared to verify the possibility of adopting the computer simulation for daylighting indoor analyses for the proposed location, beyond that, other results were obtained that were not possible with the physical scale model experiment. Possibility to apply OPV in the side window of deep plan multi-storey office buildings is evaluated.

Finally, Chapter 8 refers to general final remarks related to previous chapters contents. The references related to Chapter 2 (Introduction), Chapter 3 (Literature Review) and 8 (Final Remarks) are located at the end of Chapter 8.

As this thesis is being presented as paper collection, each of them contains its own literature review, as well as recommendation for future work and references.

Chapter 2 INTRODUCTION

Daylighting is an important strategy for improving the indoor lighting quality, user visual suitability, and in office environment, some researchers suggest greater productivity, less absenteeism, less product errors or defects, positive attitudes, less fatigue [1], and in addition, the reduction of artificial light use [2]. Daylight can provide good colour rendering and is the one light source that most closely matches with human visual response [3]. The energy potential and the cost-free character of sunlight are incentives to study this area [4].

Natural light usually enters buildings by apertures in the envelopes such as windows and skylights [5]. Side window lighting has the advantage both of providing natural ventilation in indoor environment and view to exterior landscape [2, 6], easy acquisition and installation and relatively low cost when compared to other systems, as it needs no other devices than the window itself [7]. On the other hand, they commonly cause glare, inadequate illuminance levels, and an excessive solar gain [4, 6], thus contributing to increased air-conditioning load [2]. In office buildings, for the occupants of the zones near the window, the environment view consists mainly of the window view and the illuminated surfaces nearby. On the other hand, occupants of the deeper regions of the room experience a greater luminance contrast between the internal surfaces and the façade, which can lead to a more frequent glare perception [8].

PV technology application in buildings to replace conventional building material, BIPV (*Building Integrated Photovoltaics*), increases the prospects of renewable energy systems [9]. Application of PV window into multi-story office buildings is motivated by the availability of a large area for sunlight capture, and also to compensate the fact that this construction type is associated with energy consumption and carbon dioxide emission [2, 10].

This research aims to evaluate the potential of PV side widows for deep plan multi-storey office buildings to improve daylighting distribution and glare control. For this aim, a computer simulation was carried out using Mestre, a program based on radiosity and raytracing methods, and another based on the raytracing method, Radiance. In addition, an office room scale model was built to verify data in real environment. This research intends to assist AEC (Architecture, Engineering and

Construction) practitioners at the choice of a daylighting system that can contribute to visual adequacy in deep plan multi-storey office buildings design.

2.1 PROBLEM FORMULATION

The present work aims to answer to the following research question: could the PV window be used as a lighting system capable to capture natural light, and provide its proper distribution, avoiding glare and excessive solar gains?

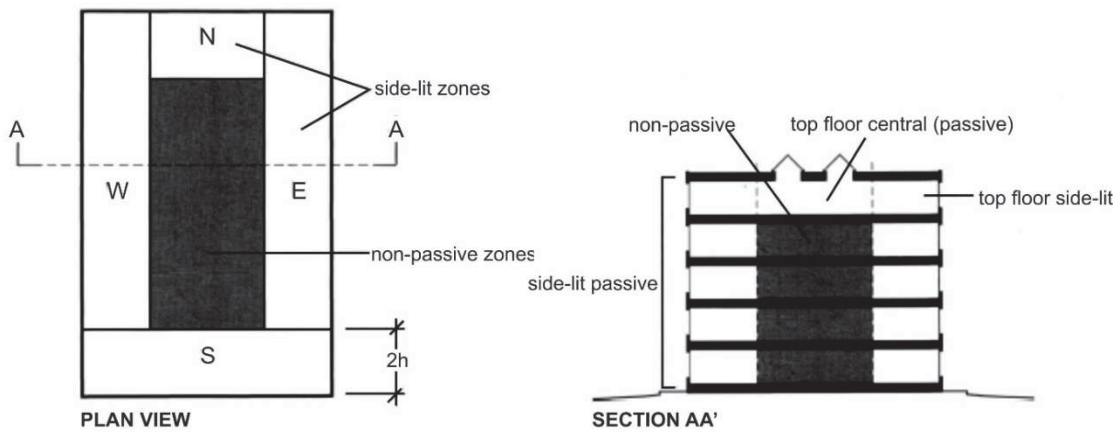
Chapter 3 LITERATURE REVIEW

3.1 DEEP PLAN DAYLIGHTING

In a business district, many office buildings are built with maximum site coverage. This can happen for two main reasons. Firstly, good cost/benefit returns to investment, given that, in this areas the land cost is expensive and individual lots are often small. Secondly, modern businesses prefer their offices to be all on one level and with normally open plans to facilitate communication and collaboration within the organization [5].

Building passive zones are spaces that can be illuminated and ventilated naturally. The passive zone depth (distance from the façade) is normally twice the floor to ceiling height [11]. Generally, spaces at distances further than the passive zone require artificial lighting for illumination. Deep plan building is considered the one that plan depth exceed the passive zone [5]. Schematic drawings from Figure 1 show the passive zones in a multi-storey building.

FIGURE 1 – PASSIVE ZONE IN MULTI-STOREY BUILDING



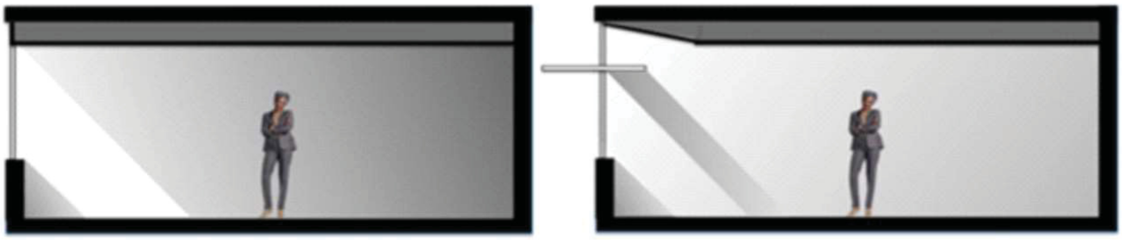
SOURCE: adapted from Baker and Steemers (2000) [11].

Deep plan buildings have a little perimeter zone to acquire daylighting and shading effects from nearby buildings contribute to sky obstructions, mainly for rooms on the lower floors [3][5]. Daylighting for buildings depends on both internal and external factors. The indoor features include window size and position, room depth and shape, and internal surfaces colours. External factors are related to ground reflectance and surrounding buildings facades [3].

3.2 DAYLIGHTING SYSTEMS

Daylight usually enters buildings through conventional vertical windows and skylights [4]. The top lighting, mainly coming from a skylight, according to Schmid (2005) [12], allows the elimination of shadows and contributes to lighting uniformity, although at the same time it causes monotony. Some of the more conventional daylighting systems are side window, light shelf and brise soleil. Figure 2 shows examples of daylighting systems: a) left: single glazing window as only light source to a deep office room and b) right: light shelf.

FIGURE 2 – DAYLIGHTING SYSTEM EXAMPLES



SOURCE: Schmid e Uehara (2017) [13].

The side window has as a benefit the observer contact with the external environment and ventilation, which are considered healthier and suitable for a prolonged stay. However, the illuminance level drops substantially along the interior depth and an illuminated plane presence in the observer's vision field can cause glare [4].

As a passive design strategy to improve indoor daylight quality, the light shelf can block direct solar radiation from the outside and bring it deeper into the indoor space through redirecting and distributing it more homogeneously throughout the room, thus, avoiding glare possibility and uneven illumination caused by direct solar radiation entering from the side [14].

The brises soleil (Figure 3) are generally external solar protection elements. They are more efficient in reducing the heat wave radiation incidence as they prevent the sun direct rays to have contact with the glass surface. However, they cause a stronger impact on the facades and are more expensive than blinds and curtains [15].

FIGURE 3 – BRISE SOLEIL EXAMPLE: MINISTRY OF EDUCATION AND HEALTH IN RIO DE JANEIRO, BY LE CORBUSIER AND OSCAR NIEMEYER, BRAZIL

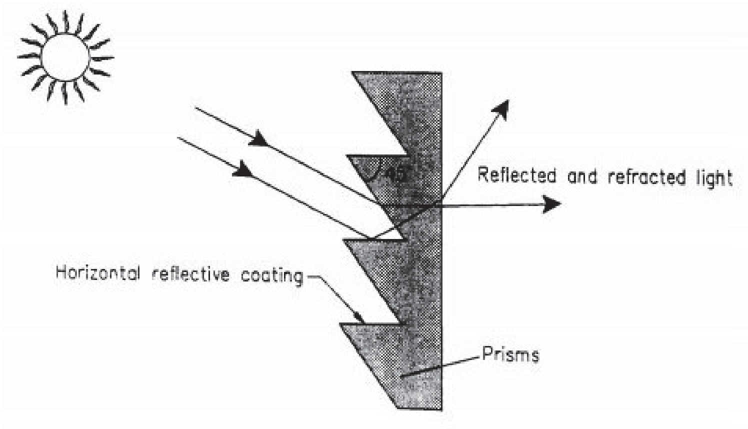
SOURCE: Fracalossi (2013) [16].

Innovative daylighting systems (IDS) typically consist of a light collector (clear optical materials, mirrors or lenses), a light guide (mirrored or branched duct, solid guide, liquid guide or optic fiber) and a diffuser (lenses, prisms or metal fins), with a possibility to combine two of them in one part. Collectors harvest direct sunlight or diffuse skylight. They could be installed on the building roof or attached at the façade. The light guide delivers the collected daylight through the building vertical voids (e.g. atrium) or via fiber optics or light pipes (ducts) [4] [17].

Special panels and glazing (Figure 4) use a special material such as prismatic glass and laser cut panel for light control. They are usually applied in side and zenith apertures, filtering and redirecting light at the time of capture. As light is emitted in the environment where the aperture is, they do not have the conduction or transport stage [4].

The prismatic surfaces redirect incident light into the ceiling and significantly improve the daylighting of areas away from the windows. The light transmission through this type of surface is done by refraction. The direction of the light rays is changed by passing through the small prisms of transparent materials [15].

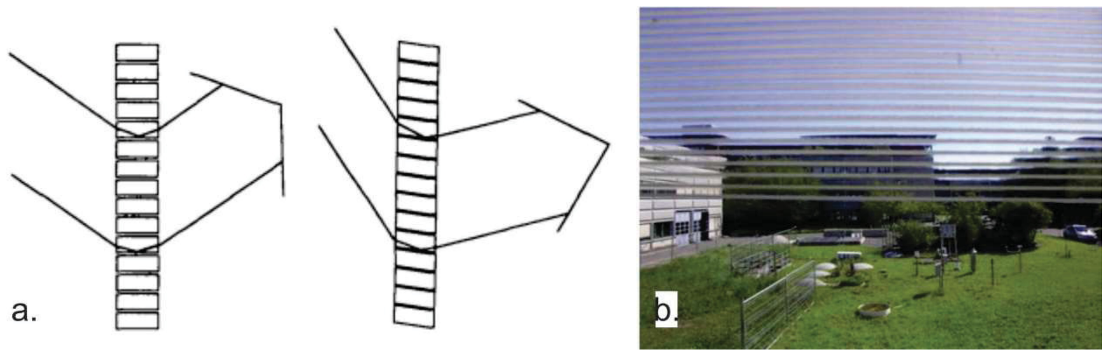
FIGURE 4 – PRISMATIC GLAZING



SOURCE: Littlefair et al. (1994) [18].

A laser cut panel (LCP) is a thin array of transparent rectangular parallelepipeds, produced by making fine laser cuts in a sheet of clear acrylic plastic with a programmable laser-cutting machine [19]. Each laser-cut performs as a small mirrored surface that reflects the daylight flux passing through the panel [20]. Figure 5.a shows a schematic diagram of an array of rectangular elements forms a light deflecting panel with good viewing transparency normal to the panel. When the internal interfaces slope in to the room incident light is deflected more deeply into the room. Figure 5.b close view through a Laser-Cut Panel.

FIGURE 5 – LCP SCHEMATIC DIAGRAM (LEFT) AND VIEW THROUGH A LCP (RIGHT)



SOURCE: a. Edmonds (1993) [21] e b. Thanachareonkit e Scartezzini (2010) [20].

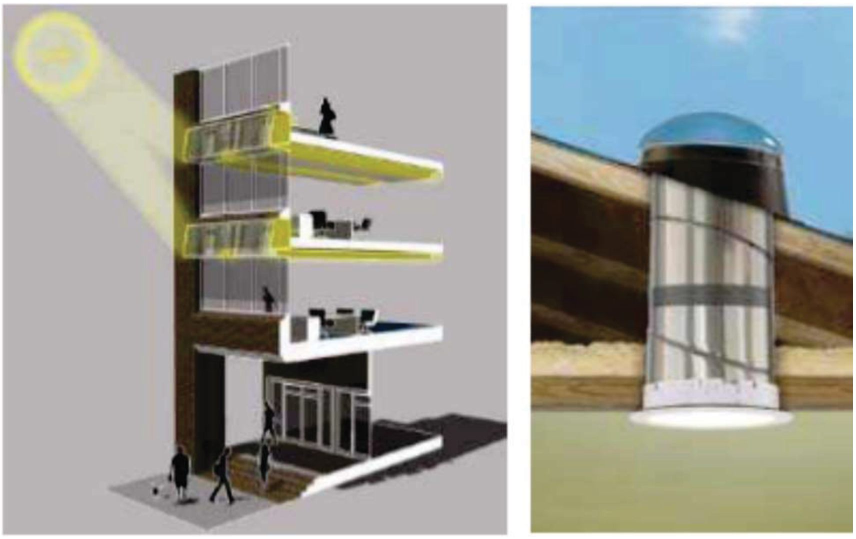
Total reflection conductors (Figure 6) use optical fibers, liquid and solid guides. Due to the fact of their total reflection they exhibit the least loss of light conduction and travel long distances with small material [4].

FIGURE 6 – TOTAL REFLECTION CONDUCTORS EXAMPLES: SOLID GUIDES (LEFT), LIQUID GUIDES (MIDDLE) AND OPTIC FIBER (RIGHT)

SOURCE: Luz (2009) [4].

The light ducts (Figure 7) can capture side or zenith light, are used horizontally and vertically, branching or not, and with or without light collector on the duct entrance. The light can be driven for long distances. Unlike other light conductors it does not use the principle of total reflection; however, it is a simple system and can be built locally in small and large constructions. This system performance is related to the reflectance of the inner coating material [4].

FIGURE 7 – LIGHT DUCT EXAMPLE



SOURCE: Luz (2009) [4].

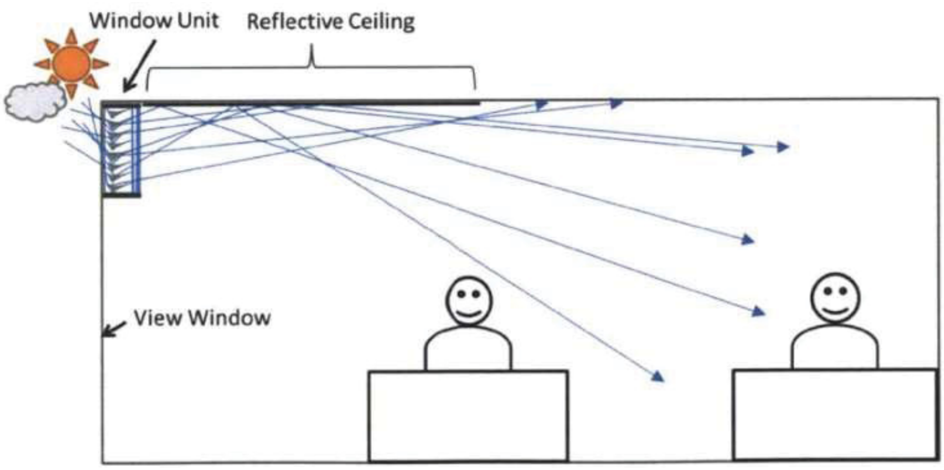
Rosemann et al. (2008) [7] developed a cost-effective solar illumination system (Figure 8) to bring natural light into the building core. This device collect sunlight, then redirect it by optical components within a canopy and distribute it within the building through light guides. Such solution could be cost-effective in volume manufacturing, could substantially reduce energy consumption which would make a significant contribution toward greenhouse gas mitigation.

FIGURE 8 – TEST FACILITY WITH SOLAR CANOPY MOUNTED ABOVE THE SOUTH WALL WINDOW (LEFT) AND INTERNAL VIEW ILLUMINATED BY THE DAYLIGHTING SYSTEM (RIGHT)

SOURCE: Rosemman et al. (2008) [7].

Thout (2011) [22] develop a passive system for use in deep-plan building spaces, which redistributes daylight incident on a building facade onto the workplane. This system consists of three sets of light redirecting elements (Figure 9): reflective louvers which collect external light and collimate it into a range of elevation angles near horizontal; cylindrical lenses which spread the collimated light in the azimuth direction to prevent glare; and ceiling tiles with a spread-specular reflectance to push light deeper into the space. For the main reference case tested (a south-facing facade with a 15º sky obstruction) this system was able to provide a workplane illuminance of at least 300 lux for 40% of annual daytime working hours at 8 m from the facade, whereas the unshaded window base case never met the 300 lux threshold at this location. With ideal conditions, the system was able to provide 450 to 500 lux at 14 m from the facade.

FIGURE 9 – SCHEMATIC VIEW OF THOUT REFLECTIVE LOUVERS



SOURCE: Thout (2011) [22].

Other novel daylighting system is the PV (Photovoltaic) window. This thesis studied this system type as it not a well-known technology in Brazil, however it is believed to have a potential to improve daylight distribution of a deep-plan office by both reducing glare and powering supplementary lighting. The next subsection explains better this thesis subject.

3.3 PV WINDOW

Photovoltaic materials can replace conventional external building materials, such as roofs, skylights or facades. This technology is called BIPV (Building Integrated Photovoltaics) [23]. Figure 10 shows BIPV application at façade with black micromorph and semi-transparent thin-film modules (left) and frameless c-Si full-roof BIPV installation (right).

FIGURE 10 – BIPV APPLICATIONS: FAÇADE (LEFT); AND ROOF AS SHINGLES (RIGHT)

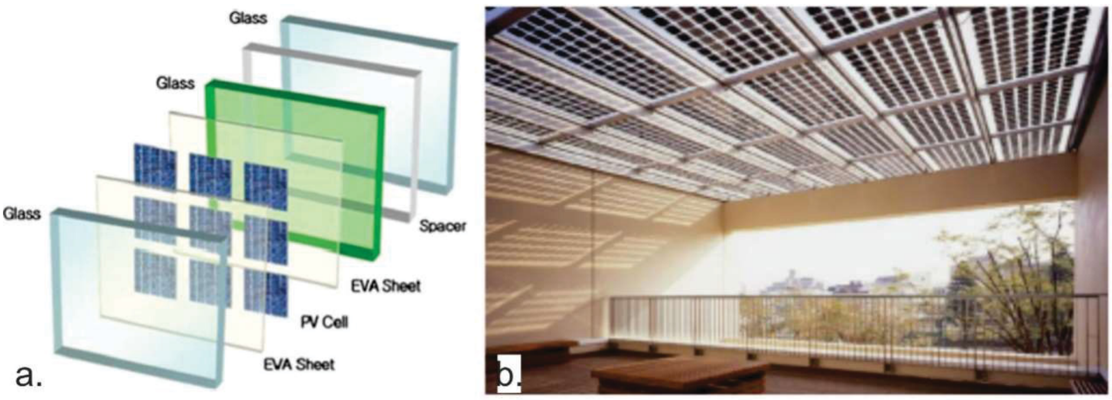
SOURCE: Heinstein et al. (2013) [24].

The PV application of windows (PVW), apart from electricity production, can reduce energy consumption in terms of cooling, heating and artificial lighting. Moreover, the PVW allows an improvement of daylighting distribution in deep plan office rooms, by controlling glare, as well as powering supplementary lighting. Therefore, it could mitigate the pollution and reduces associated costs [2] [13].

The yearly amount of harvested energy by a PV collecting, fixed surface varies according to the surface orientation. An optimization of such orientation in terms of azimuth and height angles is possible. However, it is known to not be strictly necessary, mainly due to the diffuse component of solar radiation. Ideally, for maximum capacity, PV collecting surfaces should be perpendicular to the maximum amount of solar rays. In low latitudes, solar rays are seldom perpendicular to vertical surfaces, causing PV to function at a lower capacity [25]. Nevertheless, vertical surfaces allow an easier architectural integration. Semitransparent or translucent photovoltaic technologies purposely reduce light transmission, while providing sun shading and electricity generation [2].

The most well-developed constructed by first generation common crystalline silicon (c-Si) solar cells encapsulated between highly transparent glass panes (Figure 11). Their efficiency ranges from 16–22%. Costs have been considered high until 2013, due to the high costs of silicon wafers, but have dropped since. Opaque solar cells reduce the amount of internal light and limit the external view. Light transmission characteristics and variations in temperature affect electric generation, as well as buildings cooling and heat loads. Simulation studies are needed to balance between daylighting, solar heat gain and electricity generation [2].

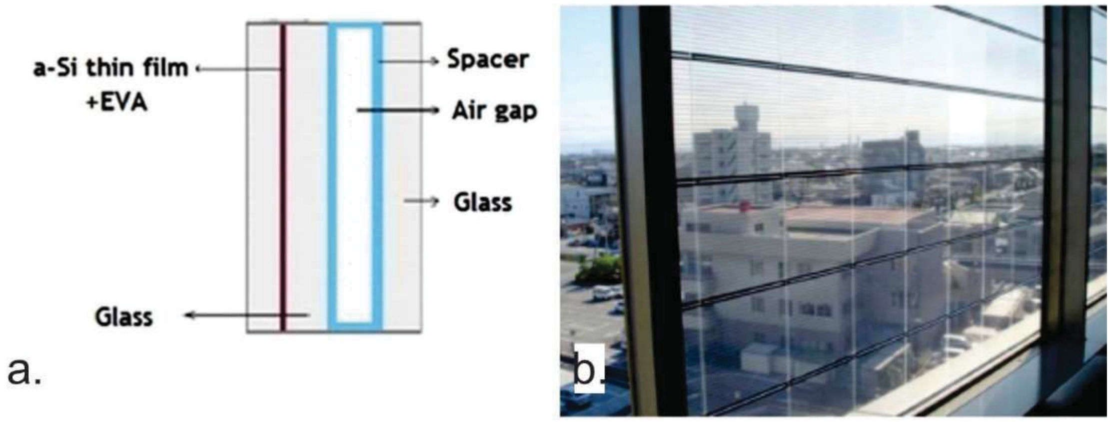
FIGURE 11 – c-SI PVW: SCHEMATIC DIAGRAM (LEFT) AND ROOF APPLICATION (RIGHT)



SOURCE: a. Skandalos and Karamanis (2013) [2]; b. Peng (2011) [23].

Another conventional PVW technology, thin film (amorphous silicon, copper indium gallium selenide and cadmium telluride) (Figure 12), is capable of increase the natural light transmission without reducing the PV efficiency. Amorphous silicon (a-Si) can be integrated on the glass with energy conversion up to 12%, while technology costs can be reduced in large-scale production. Commercial products are available with transparency up to 50%, providing more homogeneous interior daylighting than c-Si. However, due to conversion efficiency connection with visual transmittance, extensive performance optimization should be considered [2].

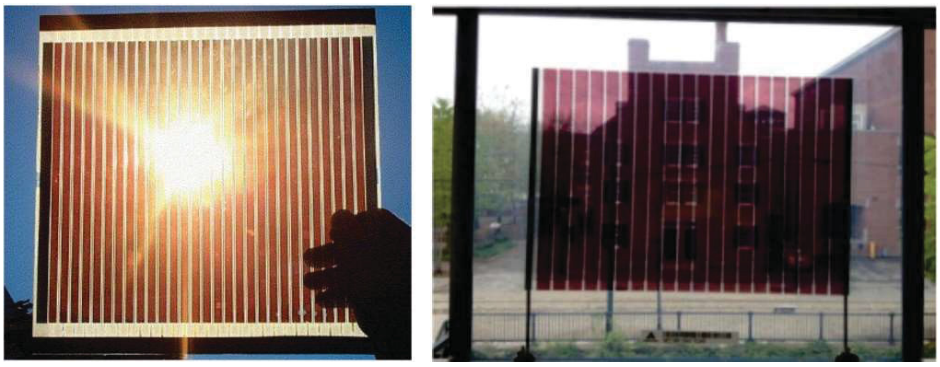
FIGURE 12 – a-SI PVW: SCHEMATIC DIAGRAM (LEFT) AND FACADE APPLICATION (RIGHT)



SOURCE: a. Skandalos and Karamanis (2013) [2]; b. Peng (2011) [23].

The emerging systems (Figure 13), dye-sensitized (DSSC) and organic solar cells (OPVs), are attractive, due to special properties such as low fabrication cost, easy scalability, simple manufacturing process, low material consumption, sensitivity to low light levels and ease of use for large area applications [2].

FIGURE 13 – PVW EMERGING SYSTEMS EXAMPLES: DSSC (LEFT) AND OPV (RIGHT)



SOURCE: Skandalos and Karamanis (2013) [2].

Although DSSC has lower efficiency in relation to other conventional solar technologies, their substrate flexibility and ability to perform with low lighting conditions and their ability to be produced in various degrees of transparency and colors give them a significant competitive advantage. Studies are still intensive regarding cell efficiency, durability and stability [2].

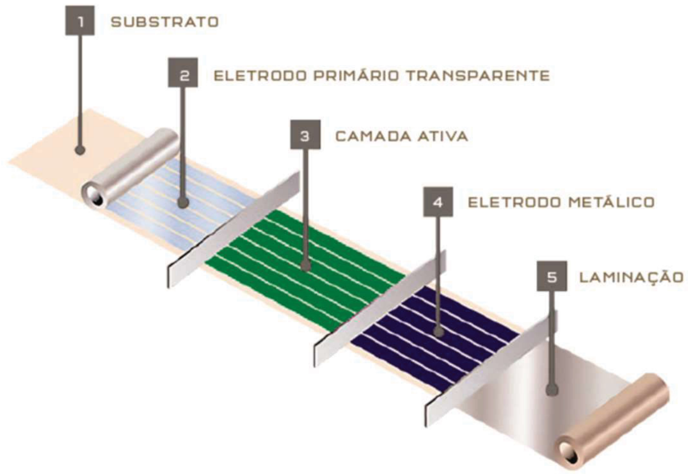
OPV is available in the market in rigid and flexible applications and can be used in greenhouses, car roofs, packaging, cell phone chargers and portable devices, bus stop coverage, roofs and windows, etc. [2] [26] [27]. Figure 14 illustrates some examples of OPV application: at a bus stop (left), at a building façade (center) and as a tree with curved polycarbonate sheets with an OPV adhesive applied (right).

FIGURE 14 – OPV APPLICATIONS

SOURCE: Paiva (2017) [28].

According to NREL (National Renewable Energy Laboratory) the current OPV efficiency is nearly 13.2% (NREL, 2017) [29]. Semitransparent OPV addressed in this research was fabricated through the roll-to-roll process with an inverted structure, totaling five layers, as shown in Figure 15.

FIGURE 15 – OPV LAYERS



SOURCE: Paiva (2017) [28].

3.4 METRICS

Hopkinson et al. [6] presented the daylighting theory, based on daylight factor (DF) concept, which states that ideal indoor illuminance values should not only be constant, but also a fraction of outside illuminance values. DF is the most commonly accepted daylight performance metric, but it has limitations in evaluating indoor daylighting on a real daylight climate, as defined under CIE standard overcast sky [30]. Alternatively, continuous daylight autonomy (cDA) is a climate-based daylight performance metric, which factors in the daylight climate of the building site and facade orientation. cDA represents a percentage of annual daylighting hours that a given point in space is daylit considering the fraction of a specified illumination level [31]. cDA uses work plane illuminance as an indicator of what share of a desired illumination level is provided by daylight in a space [32].

Glare control is just as important as ensuring sufficient illuminance levels on the work plane. Glare is considered the main manifestation of visual discomfort. It occurs when an object that is excessively bright, or brighter than the other object that we want to see, is in our field of vision [12], or in the words of Bian and Luo [33], glare may be triggered by a high luminance contrast or an inadequate luminance distribution in the observer's field of view.

Daylight Glare Index (DGI), the most commonly used metric to measure glare, was developed by Hopkinson in 1972 and considers large glare sources, such as windows [34]. The metric is based on individual’s subjective ratings from human in a daylit office space and the calculation is the sum of glare contribution of each bright source [34].

Chapter 4 METHOD

The following chapters (papers) describe the methods in a more detailed way for each research stage. This chapter justifies the method choice and presents some peculiarities of the experiments.

For the first paper, the Mestre system was chosen to evaluate the PVW performance due to the author familiarity with this tool and the possibility of creating rendered images of different window types. Two types of computer simulation were performed: static and dynamic. First one demanded the lighting parameters calculation for the Mestre data input. The second simulation considered the meteorological data files available on the Energy Plus software site for the chosen location - Curitiba, Brazil -, and the program code was changed to enable these file input. A limitation of the weather data used was noticed, and authors suggest that the Energy Plus database should be improved in order to cover the real every day's naturally lit period.

Subsequently, the second and third papers were produced simultaneously. For the second paper, an experiment was carried out with a small-scale model of a generic office room, which enabled to obtain the real daylight data for two types of sky (overcast and clear) in the city of Curitiba. The construction of a physical reduced scale model, rather than a full-size one, was chosen due to the greater control of the variables that characterize the room, the possibility of choosing the place where it would be installed and the smaller material amount required in the construction of the studied windows. The equipment obtained for the measurements was provided by the LAC (Laboratory of Built Environment) of the UFPR Department of Architecture and Urbanism and also by DiNE (Laboratory of NanoStructured Devices) of the UFPR Department of Physics. The OPV module used in the window was provided by the SUNEW company.

The first measurements made in the reduced-scale model had the purpose to adjust the procedure, such as training the team and identifying possible errors (e.g., light leakage inside the model through small holes). The sky types, clear and overcast, under which the measurements were taken, were chosen because they are two extreme sky luminance distribution conditions, easier to identify without the accurate data of a daylight metering station. In Curitiba-PR we hardly find these pure types of sky, as the most common sky condition is an intermediate one. Therefore, the measurement achievement became a difficult task.

The scale model made of raw MDF (Medium Density Fiberboard) had its internal surfaces painted. As the MDF had no treatment to be exposed to the climatic conditions, it was necessary to store and reposition the model at each new measurement. As only one model was constructed for the evaluation of the three different types of windows, the measurements were not made simultaneously, it was necessary to carry out the measurements in one type of window at a time. However, this question was solved by using a metric that takes into account these changes in the sky, daylight factor (DF), explained in the previous chapter, thus, it was possible to compare the three window types.

Another limitation of this experiment is that no tripod was used to take the pictures inside the model, thus, the HDR (High Dynamic Range) photography lost some of the quality when different images exposure were superimposed on a specific program. It was also not possible to calculate the glare index (DGI), since the size of luminance meter lens is large in relation to the model and the aperture to fit the lens would influence the illumination measurement.

The third paper uses the same conditions and parameters of the physical model experiment as input for the computer simulation. Thus, the possibility of adopting the computer simulation by Radiance was verified. That made it possible to obtain further results than those by the physical model: illuminance curves along the room depth and glare calculations. Radiance was chosen due to its ability to produce physically correct results and images that no other visualization package can achieve. As the team had no familiarity with this tool, a learning time was necessary. Also there is no database from a daylight measurement station, what made it difficult to describe the sky in Radiance, especially a clear sky. Another limitation was the characterization of the OPV material which was represented in Radiance in a simplified fashion using two materials: light-colored stripes (transparent glass) and dark stripes (dark blue glass). Results were very satisfactory; there were similarities between the experiment and the simulation results.

Chapter 5 PAPER 1

Lighting performance of multifunctional PV windows: A numeric simulation to explain illuminance distribution and glare control in offices

Desempenho da iluminação das janelas fotovoltaicas multifuncionais: Uma simulação numérica para explicar a distribuição da iluminação e o controle de brilho em escritórios

Resumo

Para mostrar como as janelas fotovoltaicas podem melhorar a distribuição da luz natural de escritório com plantas profundas, tanto na redução do ofuscamento quanto suplementando a energia para a iluminação, desenvolveu-se um experimento numérico baseado nos métodos radiosidade e raio-traçado. A geometria escolhida é uma sala de escritório de planta profunda, iluminada lateralmente. Uma mesa à 7,50 m distante da janela proporciona um plano de trabalho para a análise da iluminância. Considerou-se dez cenários: A) janela com vidro simples transparente; B) janela fotovoltaica como uma matriz de células de silício separadas, multicristalinas, montadas sobre um vidro transparente; C) janela fotovoltaica de filme fino. Respectivamente, A1, B1 e C1 são cenários sob radiação solar direta; B2 e C2 com iluminação elétrica net-zero por meio de duas luminárias; e B3 e C3 com uma luminária. A análise estática produz uma distribuição de iluminância no plano horizontal a 0,75 m acima do nível do piso ao longo de um eixo central. Observou-se vantagens nos cenários B2, C2, B3 e C3, como mostradas por imagens realísticas. Conduziu-se uma análise dinâmica para os cenários A1*, B1*, B2* e C2*. Os resultados do cálculo da iluminância anual no plano de trabalho, continuous Daylight Autonomy (cDA) e Daylight Glare Index (DGI) mostram a superioridade da janela fotovoltaica com filme fino e iluminação suplementar (cenário C2*).

Palavras-chave: Iluminação natural. Janelas fotovoltaicas. Distribuição da iluminação natural. Daylight Glare Index. continuous Daylight Autonomy. Método radiosidade. Método raio traçado. Janela fotovoltaica policristalina. Janela fotovoltaica de filme fino.

The full article can be accessed through the following website:
https://doi.org/10.1016/j.enbuild.2017.08.040

Chapter 6 PAPER 2

Evaluation of the daylighting potential of OPV windows for deep-plan rooms

Avaliação do potencial da janela OPV para iluminação natural de salas profundas

Resumo

Edifícios de escritório com múltiplos pavimentos, em sua maioria, possuem grandes superfícies envidraçadas que possibilitam aos usuários usufruir de luz e ventilação natural, além do contato do observador com o meio externo. Entretanto, sem um devido tratamento, essas superfícies podem possibilitar aumento/redução de carga térmica para o edifício, assim como causar ofuscamento nos trabalhadores. Neste sentido, a janela fotovoltaica poderia ser utilizada tanto para melhorar a distribuição da iluminação natural quanto para suplementar energia para iluminação artificial quando necessária. O objetivo dessa pesquisa é avaliar o potencial da aplicação de Dispositivos Orgânicos Fotovoltaicos (OPV) em janelas laterais de edifícios de escritórios com múltiplos pavimentos e salas profundas, a fim de verificar a sua contribuição em relação à qualidade da iluminação natural no ambiente interno. Realizou-se a avaliação por meio de um experimento com um modelo em escala reduzida de uma sala de escritório genérica, iluminada por uma janela lateral, a qual corresponde a 100% da área da fachada Norte. Compararam-se três tipos de materiais para a janela sob condição de céu real (nublado e claro) em Curitiba-PR: Cenário A - vidro simples 3 mm; Cenário B – vidro e OPV; e, Cenário C – vidro com aplicação de película solar. Apesar da redução da iluminância com a utilização dos materiais dos cenários B e C em relação ao material dos cenários A, constatou-se uma melhor distribuição da iluminação natural no interior da sala, sendo que no cenário B existe a possibilidade de utilizar a energia gerada na janela fotovoltaica para a iluminação artificial.

Palavras-chave: Iluminação natural. Janela fotovoltaica. Dispositivo fotovoltaico orgânico. OPV.

The full article can be accessed through the following website:
https://doi.org/10.20396/parc.v10i0.8652752

Chapter 7 PAPER 3

Daylighting evaluation in deep plan office buildings with OPV windows through simulation on Radiance

Avaliação da iluminação natural em salas profundas de edifícios de escritório com janela OPV por meio de simulação no Radiance

Resumo

Esta pesquisa tem como objetivo avaliar o potencial de aplicação da janela OPV (OPVW) em edifícios de escritório com múltiplos pavimentos e planta profunda, a fim de verificar sua contribuição para a qualidade da iluminação natural interna. A janela OPV é uma tecnologia de baixo custo e impacto ambiental reduzido, indicada para aplicação em edifício de escritórios com múltiplos pavimentos devido ao seu potencial de adaptação a diferentes configurações arquitetônicas, leveza e transparência, etc. Em um estudo anterior desenvolvido pelos autores, realizou-se experimento com modelo em escala reduzida de uma sala de escritório genérica. Comparou-se três tipos de materiais para a janela, sob condições de céu real (nublado e claro): vidro simples de 3 mm (cenários A); vidro simples com OPV (cenários B); e vidro simples com aplicação de película de controle solar (cenários C). No presente estudo, os mesmos parâmetros do experimento foram utilizados como entrada para simulações no Radiance e os resultados foram comparados com os anteriores (iluminância no plano de trabalho, fator de luz do dia e fotografias do interior do modelo). Encontramos semelhanças entre eles. Assim, outros resultados foram produzidos: curvas isolux, DGI e imagens renderizadas. As imagens renderizadas mostram uma visão mais brilhante nos cenários A em comparação com os cenários B e C. Mesmo que a iluminância média seja reduzida, obtém-se uma melhor distribuição da luz do dia e uma redução do ofuscamento. DGI indica brilho perceptível para alguns cenários A. Por outro lado, na maioria dos cenários B e C, o brilho estava abaixo da faixa perceptível. Além disso, os cenários com OPVW (cenários B) ainda apresentam mais uma vantagem: a produção de energia para iluminação artificial quando os valores de iluminância não são suficientes.

Palavras-chave: Desempenho visual. Simulação Computacional. Curvas isolux. Daylight Glare Index. Render images.

The full article can be accessed through the following website:
https://doi.org/10.4025/actascitechnol.v44i1.58823

Chapter 8 FINAL REMARKS

This thesis studied three photovoltaic window types, two conventional, polycrystalline and thin film, and another unconventional, OPV. The aim was to evaluate the application potential of photovoltaic windows to open plan multi-storey office buildings, to verify their contribution to the daylighting quality of indoor spaces. This research is divided into three papers. The first one compares photovoltaic windows, polycrystalline and thin film with a single glass transparent window. The second and the third papers compare OPV window with a single glass transparent window and with a solar protection film applied on single glass transparent window. To keep DF high and to limit glare from a worker sitting in a place away from the window was the main goal.

In the research, small work plane illuminance values were observed for photovoltaic windows scenarios as compared to the direct gain single glass window scenarios. However, the single glass window also presents high illuminance and DGI values; there is a high probability of glare for an observer sitting far from the window, mainly during the winter months, as the first paper shows.

Also, in the first paper, the comparison between polycrystalline and thin film photovoltaic windows shows the thin film window superiority in terms of work plane illuminance, continuous daylight autonomy (cDA) and glare index (DGI) values.

The second paper uses a physical reduced scale model and the third paper uses computer simulation to compare the OPV window (scenario B) with a single glass window (scenario A) and a solar protection film applied on single glass transparent window (scenario C). Multi-storey office buildings with a glass curtain-wall frequently use a solar protection film for glare control. In these researches (second and third papers) similarities were observed between the OPV window and the solar protection film applied to a single glass, transparent window in terms of daylighting distribution and glare control: a slight advantage was identified in the DF and DGI values for the OPV window, besides the capability this one has to be integrated with the electric lighting installation when daylighting levels were not sufficient.

The scale model experiment (second paper) results show the OPV advantage over the other window materials as it allows a slightly greater illuminance at points away from the window. It also made it possible to measure daylighting inside the room under real sky conditions (overcast and clear). These results were used as parameters to validate the simulation results (third paper) and proven the similarity between them, and thus additional data were produced: images with illuminance curves and glare index calculation, DGI.

The computer simulation results show higher DF values for A scenarios when compared to other window materials, it does not mean a higher lighting quality, because daylight is not distributed homogeneously, it creates a higher contrast between the areas close to the window and the areas at deep regions of the room, that may cause glare to the room users. Render images reveal a greater contrast for scenarios A and a better daylighting distribution for scenarios B and C. Higher DGI values were calculated for scenarios A and some of them reached the range of 24-31, classified as disturbing glare and requiring countermeasures. On the other hand, DGI values for scenarios B and C stay above the perceivable range. Similarities were found between the measurement results with the reduced model and the computational simulation. Although systematic study and optical properties optimization of semitransparent OPV window are still scarce and only at an initial state, this material is attractive due to low production cost, flexibility for application in complex surfaces, etc. [10]. A low cost OPV technology utilization could potentially reduce building energy load and mitigate pollution in an appreciable scale [10].

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