MASTER

Building performance evaluation of integrated transparent photovoltaic blind system by a virtual testbed

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Building Performance Evaluation of Integrated Transparent Photovoltaic Blind System by A Virtual Testbed

Msc thesis

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Abstract

The purpose of this study is to investigate the building performance of an innovative shading system using for double skin façade type buildings. The subject of the research is an integrated transparent photovoltaic blind (ITPVB) system which can transmit diffuse sunlight and concentrate direct radiation for electricity generation. A testbed based on the theatrical processes of ITPVB and building simulation tools has been created and proven to be trustful in a large extent on aspects of thermal and electrical performance. The results of a simulation model of a standard office room using ITPVB reveals that ITPVB has a large potential on energy saving and leading buildings to be zero energy building with acceptable thermal comfort level at the most of the working hours. The results from the testbed give this kind of under developing products an opportunity to know the possible performance even when the product is on a conceptual phase.

**Keywords:** shading system, CPV, climate adaptive building shells, building performance, building simulation, innovative building element, products’ design phase, ZEB
Definition list and explanation

- **ITPVB**: Integrated transparent photovoltaic blind
- **Slat**: the pieces in ITPVB or slat-blind, which can be switched to a certain angle, one window can be covered by many slats
- **(Solar) cell**: one component of ITPVB (the dots in Figure i); the part where concentrates direct radiation in ITPVB
  Module: one component of ITPVB (the area with line patterns, not including dots); the part where is transparent and transmits diffuse sunlight.

![Figure i Geometry of ITPVB slat](image)

- **Lens**: the main material of the module, which gathers the direct radiation on the solar cell
- **DSF**: double skin façade
- **ZEB**: zero energy building
- **ESP-r**: a building performance simulation tool
- **TMC**: construction type in ESP-r, transparent multi-layer construction
- **MLC**: construction type in ESP-r, multi-layer construction
- **CFC**: construction type in ESP-r, complex fenestration construction
- **HDD**: heating degree day
- **CDD**: cooling degree day
1. Introduction

Energy and comfort are among the biggest concerns in the building industry when considering about building physics and services. On building performance point of view, the fenestration construction is the weakest part of the building due to the possible cause of overheating, glare and infiltration. Too much incident direct solar radiation on fenestration leads to glare and overheating, which reduces visual and thermal comfort and increases energy consumption for cooling. Thus, shading devices become to be an essential and efficient building system to improve visual and thermal comfort, and decrease cooling demand at one time by sunlight control. Direct radiation is the source that causes glare. Shading devices, such as slat-blinds, reflect part of direct radiation and scatter the rest of incident direct radiation to be diffuse radiation that brings a soft visual effect. The design of a shading device should balance the daylight requirement versus the need to reduce solar heat gain (Tzempelikos and Athienitis 2007). However, there are two drawbacks of conventional shading devices, such as venetian blinds, roller blinds and curtains. Conventional shading devices reduce the pleasuring view of nature due to common used opaque shading material. Thus, shading devices made of transparent material were invented (B.I.Seeger 1969). The special feature of it is that it can reflect the direct radiation and transmit the diffuse radiation to control the sunlight. Conventional shading devices reflect the majority of incident solar radiation which can be used for power generation. However, there are very few researches about development of a shading device which can generate power. Although, transparent slat-blinds are invented to provide see-through views for users. The multiple solutions of improving the drawbacks of conventional shading devices, mainly for power generation are still under discussion.

1.1 Background

Solutions for on-site solar energy use for building

Using renewable energy and reducing energy demand are the keys for energy saving. Solar energy, as one of the most powerful renewable energy sources, is widely used for power generation. On-site solar systems, such as building integrated photovoltaic (BIPV), are more and more popular in the building industry (A. J. Marszal et al. 2012). According to (Prasad & Snow et al. 2005), BIPV brings many benefits for users and investors on economic, feasibility, utility, greenhouse gas reduction, building structure, architectural elegant and public expression. They are widely applied on Zero Energy buildings (ZEB), especially for the projects located in hot climate countries.

As it is known, solar radiation has incredibly strong power. In the recent centuries, photovoltaic has been used more and more often to generate energy due to the highly increased efficiency. BIPV is using photovoltaic material to replace conventional building material. BIPV has been encouraged to use in many countries. USA, China, France, Spain and so on have bonus from their governments for BIPV projects [web-1]. Except the profit from electricity generation, peak heating and cooling load of air-gap BIPV projects are also lower than conventional projects according to simulation (Wang et al. 2006). By the invention of translucent photovoltaic (Baig et
(Sabry, Abdel-hadi, and Ghitas 2013)(Quesada et al. 2012), conventional glass windows can be replaced. A study results in 33.5% energy saving by using semi-transparent photovoltaic as BIPV project in Abu Dhabi (Ardente et al. 2005). Apart from semi-transparent photovoltaic, concentrated photovoltaic (CPV) as well can form translucent solar façades and skylights. The transparent component is the lens for gathering solar radiation on solar cell. In a high concentrated photovoltaic, the solar cell is very small. The visual effect of a whole piece of photovoltaic module is see-through. It uses Fresnel lens that can only concentrate direct radiation. Thus, diffuse light can be transmitted. In this decade, increasing research interests focus on the optical performance and development of transparent CPV façade. However, most of the researches, the CPV façades use low concentrated photovoltaic. It concentrates both direct and diffuse radiation and allows solar rays transmitting from none-PV part on the module. The optical efficiency varies with the angle of sun tracking system. As well to avoid direct radiation, BIPV formed as shading device absorbs the majority of incident solar radiation instead of reflecting it. Notwithstanding, BIPV as shading device has a longer payback time comparing to standard PV laminates (James, Jentsch, and Bahaj 2009) due to the decreased efficiency from shades by above photovoltaic panels (Yoo and Lee 2002)(Kang, Hwang, and Kim 2012). With certain distance and higher PV efficiency, the added value of BIPV as shading devices will benefit the building.

On one hand, we try to avoid too much strong direct solar radiation to enter inside of the building. On the other hand, we try to collect solar energy for power generation as much as possible to benefit the building. Therefore, the concept of a system, which can generate power from solar energy and meanwhile increase visual and thermal comfort values, becomes to be one of the hottest topics in solar energy using in the building industry. Semi-transparent photovoltaic (D. H. W. Li, Lam, and Cheung 2009)(Miyazaki, Akisawa, and Kashiwagi 2005)(Wong et al. 2010)(Wah et al. 2005)(Maran 2011), photovoltaic as shading devices (Kang et al. 2012)(James, Jentsch, and Bahaj 2009), smart energy glass (R. C. G. M. Loonen et al. 2010) and translucent CPV façade (Quesada et al. 2012)(Sabry, Abdel-hadi, and Ghitas 2013) have been investigated and resulted as large potential to add values on thermal performance, energy saving and cost performance to a building. Inspired by the translucent CPV and traditional shading devices, an innovative concept of an integrated transparent photovoltaic blind (ITPVB) system is currently under development by SolarSwing®. This dynamic and complex system can make much potential referred to the researches on other topics of transparent photovoltaic and blind systems. Table.1.1 shows an overview of the shading and BIPV products/concepts and their functions. The overview presents that the development of shading, BIPV and transparency construction becomes more integrated. The integration also makes the one product has more functions at one time. ITPVB fulfil the gaps between shading devices, BIPV and transparent construction.

**Integrated transparent photovoltaic blind (ITPVB)**

Integrated transparent photovoltaic blind (ITPVB) system is an advanced combination of transparent blind (B.I.Seeger 1969), BIPV formed as blind (Kang, Hwang, and Kim 2012) and transparent BIPV using Fresnel lens for concentration of solar radiation (Tripanagnostopoulos, Siabekou, and Tonui 2007)(Sabry, Abdel-hadi, and Ghitas 2013)(Yamada et al. 2011)(Fig.1.1). ITPVB consists of transparent photovoltaic module and cell as slats. Because of the function of
the Fresnel lens (Fig.1.2b), direct solar radiation is concentrated on solar cell and diffuse solar radiation is transmitted (Fig.1.2a and b). Thus, ITPVB can bring soft daylight by diffuse radiation to indoor and transfer direct radiation to electricity. ITPVB is considered to be installed in-between a double skin façade (DSF) to protect the products. For an under development phase of this state of art innovative product, the performance of the product can be calculated or measured by experiments. However, to discover the dynamic product performance on the whole building level by calculation and experiments spends much more efforts. Building performance simulation is an approach to figure out energy efficiency and comfort level in a building. Considering the product’s design and market values, prediction of its building performance is vital for development and improvement. Since ITPVB is a new system to the building industry, there is no suitable building performance simulation tool to predict its behavior. The study of building performance of ITPVB gives many possibilities, interests and difficulties. The building simulation can help the developer have insights for this kind of products’ feasibility, decision-making in development, improvement, and market focus (R. C. G. M. Loonen et al. 2014). This study also gives researchers a guide and inspiration for one-step further work in the future.

Table 1.1 The overview of the shading and BIPV products/concepts and their functions

<table>
<thead>
<tr>
<th>Product/concept</th>
<th>Generate Electricity</th>
<th>Prevent glare</th>
<th>Reduce solar heat gain</th>
<th>Deliver diffuse light</th>
<th>Dynamic tracking</th>
<th>Transparent</th>
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<tbody>
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<td>Roller-blind (Joong 2011)</td>
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<td>Curtain (Joong 2011)</td>
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<td>Slat-blind (Baldinelli 2009)</td>
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<td>Overhang</td>
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<td>Transparent slat-Blind: Solar Swing reflect (Web-2)</td>
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<td>BIPV: opaque roof/façade (Mei et al. 2003)</td>
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<td>BIPV: CPV (Tsoutsou et al. 2014)</td>
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<td>BIPV: Semi-transparent PV (D. H. W. Li, Lam, and Cheung 2009)</td>
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<td>BIPV: CPC (Sabry, Abdel-hadi, and Ghits 2013)</td>
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<tr>
<td>BIPV: opaque shading device (slat-blind) (Kang, Hwang, and Kim 2012)</td>
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<tr>
<td>BIPV: opaque shading device (passive shading) (James, Jentsch, and Bahaj 2009)</td>
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<td>Smart energy glass (R. C. G. M. Loonen et al. 2010)</td>
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<tr>
<td>ITPVB: Solar Swing Energy (Web-2)</td>
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Fig. 1.1 Inspiration and history (from slat blind and BIPV to ITPVB) of ITPVB (Blue arrows present integration, red arrows present development)

Fig. 1.2a. How ITPVB benefits the building

Fig. 1.2b Fresnel lens to concentrate direct radiation (solid line) and transmit diffuse radiation (dash line). (Tripanagnostopoulos, Siabekou, and Tonui 2007)
1.2 Research questions

The objective of this study is to investigate building performance of an integrated innovation in the building industry to support the product development. Developing a proper model to simulate building performance of the state of art innovative building element is an essential step for this study. Three research questions are addressed to fulfil the detail of the objective.

1. How to predict the building performance of this innovative building element and then ensure the quality of the prediction?

2. How is the solar radiation distribution through the ITPVB in-between the double skin façade compared to the double skin façade without any shading devices and with slat-blind in-between?

3. How is the building performance with different climate types, orientation, thermal mass, and ITPVB’s coverage in comparison to conventional shading measures on aspects of energy performance and thermal comfort level?

1.3 Methodology

Building performance can be analyzed by theoretical calculation, experiments, building simulation software and multiple uses of the above methods. In this study, ITPVB is still on the developing phase. ITPVB has not been produced yet. For this reason, experiments cannot be done. The methodology of this study focuses on theoretical study and building simulation software.

Analysis of ITPVB by theoretical study

Well-understanding of the research object is critical before building performance simulation. For the concept, figuring out what processes relevant to building performance happen in ITPVB system is imperative. During the investigation of processes in ITPVB, a climate research about solar direct radiation and diffuse radiation helps to have a better understanding of the system and indicates the possible influences to ITPVB system. A rough estimation of energy flow in ITPVB in-between double skin façade can be calculated as a reference for the test results from model development phase simulation. After having clarified the physical principles and heat transfer mechanism of ITPVB system, a suitable simulation tool can be chosen to implement the proper model for ITPVB.

Implementation ITPVB into a dynamic building simulation

From the theoretical study, the process is indicated by equations. Matching the specific process of ITPVB with the chosen software’s theory indicates the insight of implementation of ITPVB into a dynamic building simulation. A test model with simple geometry and basic control rule works for implementation and verifying if the implementation is correct. By analysis of specific indicators of this fenestration component and comparison with the rough estimated results from theoretical models, the quality of model development can be ensured.
Building simulation of ITPVB
As long as the developed model for ITPVB can be trusted to an acceptable extent, case studies of the influences of the building and environment (building orientation, climate types, thermal mass and ITPVB’s coverage) are compared with each other. Moreover, the same cases of slat blind in-between DSF are also compared with ITPVB in-between DSF on the reference of cases of DSF without any shading devices.
2. Analysis of ITPVB by theoretical study

This chapter presents a theoretical study about the ITPVB in-between double skin façade. In addition, it gives the research of diffuse and direct radiation of different locations. Thus far, combing the solar radiation and theoretical study, it presents the conceptual models for simulation.

2.1 Diffuse and Direct solar radiation

Direct radiation describes solar radiation traveling on a straight line from the sun down to the surface of the earth. On the other hand, diffuse radiation is solar radiation scattered by molecules and particles in the atmosphere (e.g. clouds). Diffuse radiation does not have a definite direction but travels in all the directions. In a clear sunny day, the direct radiation is around 85% of total solar radiation, and the diffuse radiation is about 15%. In an extremely overcast day, 100% solar radiation can be diffuse radiation. Direct/diffuse ratio is changing by the climate, latitude and seasons. Diffuse radiation ratio is much higher in higher latitude, cloudier places than in lower latitude, sunnier places. Abu Dhabi, which has a low diffuse radiation ratio, has an extreme case with low latitude and sunny weather. However, the diffuse radiation of four locations: Amsterdam, Warsaw, Madrid and Abu Dhabi are very close on hourly data (Fig.2.1b). This study of diffuse and direct radiation of different locations works as a preparation for investigating the relevance between solar radiation circumstance and building performance of ITPVB.

Fig.2.1 Monthly direct and diffuse radiation of locations with different climates and latitudes through a year
2.2 Conceptual models

There are three parts of physics of ITPVB determining the building performance: optical, thermal and electrical parts. The theoretical study of these three parts helps to have a thorough understanding of its physics. However, optical performance is not in the scope of this study. The focuses are on thermal and electrical models.

2.2.1 Optical model

Optical model is used to predict the visual performance. The visual performance determines the use of artificial lighting and shading. How much percent artificial lighting is used influences casual heat gain from lighting. The optical model is based on the optical properties of the used material of fenestration elements, such as transmittance and reflectance. The optical properties can be tested by experiments and then calculated. However, there is no products/sample produced yet. The only known part of the optical model is that ITPVB consists of transparent slats with very tiny metal dots (CPV cells).

2.2.2 Thermal model and Electrical model

Thermal model is used to indicate the thermal behavior of the object. The thermal behavior determines heating and cooling load of a building. The impact of fenestration elements on the building’s energy is based on the location of the window, its size, construction (including cavity, frame, spacers etc.) and optical properties of the glazing (Loonen 2010). Temperature driven heat transfer and solar heat gain are two heat transfer processes contributing to the thermal energy flow. Heat gain or loss through fenestration elements is caused by convection, conduction and radiation of the difference between indoor and outdoor temperature. Solar heat gain is caused by solar radiation processes. ITPVB has much influence on solar heat gain of the fenestration element because of the treatments of solar radiation processes. However, the outside and inside temperatures are dominated by environment and indoor HVAC system. Thus, solar heat gain and its processes are vital to be analyzed comprehensively.

On the other hand, electrical model contributes to estimate the electricity generation from CPV cell. The source of electricity generation is also solar radiation. In this model, concentration is the main feature of this model. Related with solar radiation process, the prediction can be completed.

Solar heat gain

Transparent fenestration elements are the main entrances of solar heat gain for the building. Treating a fenestration element as a black box and imposing equal outside and inside temperature, the energy flow from outside to inside through a fenestration element only consists of solar fluxes. Fig.2.2a shows the components of heat gain through a conventional fenestration element. Indoor solar heat gain is from three solar fluxes: transmitted solar flux, long-wave radiation flux and convective flux. Long-wave flux and convective flux are from the absorbed solar flux. Nevertheless, ITPVB has another energy path for absorbed direct solar radiation, which is
electricity generation (Fig. 2.2b). Thus,

\[ Q_{\text{ITPVB, a, dir}} = Q_{\text{ITPVB, h, dir}} + Q_{\text{ITPVB, el, dir}} \]

Where, \( Q_{\text{ITPVB, a, dir}} \) is absorbed direct radiation on ITPVB slats [W];
\( Q_{\text{ITPVB, h, dir}} \) is absorbed direct radiation on ITPVB slats contributing to heat gain [W];
\( Q_{\text{ITPVB, el, dir}} \) is absorbed direct radiation on ITPVB slats contributing to electricity generation [W].

Fig. 2.2a Components of heat gain through a conventional fenestration element (Lomanowski 2008)

Fig. 2.2b Components of heat gain through ITPVB in-between double skin façade
**Solar radiation processes of ITPVB in-between double skin façade**

Radiation has reflection, absorption and transmission when it hits on a surface. Complicated radiation processes happen in the air gap of a double skin façade due to the reflected radiation goes through a 2\textsuperscript{nd} reflection, absorption and transmission process. Shading devices in-between double skin façade makes more complex processes from 2\textsuperscript{nd}, 3\textsuperscript{rd} and more reflection radiation. Fig.2.3a,b explain the solar radiation processes of slat-blind and ITPVB in-between double skin façade respectively. In Fig2.3a,b, it only shows one direct of diffuse radiation when it hits on double skin façade surface instead of every direct for a clear demonstration of one solar ray’s reflection, absorption and transmission process. Solar radiation is reflected and absorbed by every layer of the fenestration. Slat-blind as well scatters direct radiation to be diffuse radiation. Therefore, only diffuse radiation is transmitted to indoor. Depending on reflection and transmission fraction, part of radiation is reflected by outer layer glass and part of radiation is absorbed by each layer. The absorption and reflection fraction of direct and diffuse radiation is the same for slat-blind but different for ITPVB. For ITPVB, majority of direct radiation is absorbed by slats. Part of the absorbed radiation is used to generate electricity. The absorption fraction of diffuse radiation is very small, but the transmission fraction is large so that the majority of diffuse radiation can be transmitted.

Fig.2.3a,b. Solar radiation reflection, absorption and transmission processes of slat blind (2.3a.) and ITPVB(2.3b) in-between double skin facade (red solid ray presents direct solar radiation; orange dash ray presents diffuse solar radiation at a certain direction)

**CPV Concentration**

ITPVB uses concentrated photovoltaic cells for electricity generation and the Fresnel lens for transparency, delivery of electricity and diffuse rays respectively. Therefore, for the ideal concentration, all of the absorbed direct radiation is gathered on a CPV spot. This phenomenon would increase the intensity of solar radiation hit on the module surface by concentration ratio. The intensity of solar radiation is called irradiance. Concentration ratio can be calculated by the ratio of module area and cell area. The electricity output is determined by CPV efficiency and incident irradiance. This process can be expressed as:
\[ E_{\text{ITPVB,a,dir}} = \frac{A_{\text{module}}}{A_{\text{cell}}} \times E_{\text{ITPVB,a,dir,m}} \]

\[ E_{\text{ITPVB,a,dir,m}} = \frac{Q_{\text{ITPVB,a,dir}}}{A_{\text{module}}} \]

\[ q_{\text{ITPVB,el}} = \eta \times E_{\text{ITPVB,a,dir}} \]

\[ q_{\text{ITPVB,h}} = (1 - \eta) \times E_{\text{ITPVB,a,dir}} \]

Where, \( Q_{\text{ITPVB,a,dir}} \) is absorbed direct radiation on ITPVB slats [W];
\( E_{\text{ITPVB,a,dir,m}} \) is absorbed direct irradiance on ITPVB slats (module) [W/m²];
\( E_{\text{ITPVB,a,dir}} \) is absorbed direct irradiance on ITPVB CPV cell [W/m²];
\( A_{\text{module}} \) is the area of ITPVB slats (module) [m²];
\( A_{\text{cell}} \) is the area of ITPVB CPV cell [m²];
\( q_{\text{ITPVB,el}} \) is electricity generation of ITPVB [W/m²];
\( \eta \) is CPV efficiency of ITPVB;
\( q_{\text{ITPVB,h}} \) is heat flux caused by absorbed direct radiation on ITPVB slats contributing to heat gain [W/m²].

Apart from the contribution to the electricity model, the concentration of CPV will also increase the surface temperature of solar cell. The effective surface temperature of a surface can be calculated by (Wit 2009):

\[ T_{\text{rev}} = \left( h_{\text{ev}} T_{a} + h_{r} T_{r} + \sum \alpha_i E_i - \epsilon \Delta E_{\text{at}} \right) / \left( h_{\text{ev}} + h_{r} \right) \]

Where, \( h_{\text{ev}} \) is the surface coefficient of convective heat transfer [W/m²K]
\( h_{r} \) is the surface coefficient of radiative heat transfer [W/m²K]
\( T_{\text{rev}} \) is the effective surface temperature
\( T_{a} \) is the air temperature near the surface
\( T_{r} \) is the 'mean' radiant temperature perceived by the surface
\( \alpha_i \) is absorptivity of the surface for radiation of source j [-]
\( E_i \) is the irradiance of radiant source j (sun, lighting) [W/m²]
\( \epsilon \) is emissivity of the surface [-]
\( \Delta E_{\text{at}} = \sigma T_{4}^{4} - E_{\text{at}} \) with \( E_{\text{at}} \) the atmospheric radiation (outdoors)[W/m²]

Thus, the CPV cell has a high temperature, and the surface temperature of the module has a lower temperature. Then, conduction and convection by the temperature difference happens on a vertical surface (from cell to the edge of the module). The thermal model should consider about this part of heat transfer as well. Therefore, the heat gain should be:

\[ Q_{\text{heat gain}} = Q_{t,\text{dir}} + Q_{\text{cv, glass,a,h}} + Q_{\text{cv, ITPVB,a,h}} + Q_{\text{lw, ITPVB,a,h}} + Q_{\text{lw, glass,a,h}} + Q_{\text{cd,cv,m,c}} + Q_{\text{o,i}} \]

Where, \( Q_{t,\text{dir}} \) is transmitted diffuse irradiance [W];
\( Q_{\text{cv, glass,a,h}} \) is convective flux by glass’ absorbed solar irradiance [W];
\( Q_{\text{cv, ITPVB,a,h}} \) is convective flux by ITPVB’ absorbed solar irradiance contributing to heat gain [W];
$Q_{lw, ITPVB, a, h}$ is long-wave flux by ITPVB’s absorbed solar irradiance contributing to heat gain [W];
$Q_{lw, glass, a, h}$ is long-wave flux by glass’ absorbed solar irradiance [W];
$Q_{cd, cv, m, c}$ is conduction and convection flux from ITPVB’s cell to module [W];
$Q_{o, i}$ is heat flux caused by difference between outdoor and indoor temperature [W].

The algorithm of heat flux caused by long-wave radiation and convective flux can be referred from slat-blind in-between double skin façade. It is because the geometry of ITPVB and slat-blind are very similar, and the features of ITPVB does not influence air cavity referring to slat-blind. Moreover, long-wave radiation is opaque to almost all materials. However, because of the gap between each two slats, the long-wave radiation to slat-blind and ITPVB can be considered as semi-transparent (Lomanowski 2008).

Thus, the thermal model and electrical model are clear enough for preparation of developing a proper model for ITPVB in-between double skin façade.
3. Implementation to dynamic simulation model

3.1 Performance indicator

For the implementation of ITPVB into dynamic simulation model, the performance indicator should consider two aspects. One indicates the component performance of ITPVB in-between double skin facade to assess the success of the implementation. The other should indicate the building performance of a building/room with this component. The performance indicators expressed in values is used to assess how well the subject behaves. For the component, the focus is on how much direct radiation can be concentrated, how much diffuse radiation can be transmitted to the indoor and how much solar radiation can be absorbed in the component and then transform to be solar heat gain and to be electricity respectively. For the building, the initial focus is on how the building behaves on energy that consists of space heating and cooling loads and electricity generation. In a simplified case, the building performance can be explained by the component performance. Thus, in this chapter, solar radiation distribution through the component and space heating and cooling load and electricity generation are used as performance indicators.

3.2 Selection of simulation software

On account of the importance of development of the proper model, the simulation tool becomes to be the first step after a well understanding of the system. Currently, none of the existing simulation tools can treat diffuse and direct radiation separately for a fenestration construction. For this reason, a modification of an existing simulation tool is needed. Out of the mostly used simulation software, ESP-r has an open source code environment for developers.

3.3 Standard ESP-r’s abilities and limitation for ITPVB model

ESP-r is a worldwide used building simulation software with an open development community to developers. It gives opportunities to model an innovative building component or system by modifying the source code files. A standard ESP-r can model the thermal, visual and acoustic performance as well as to estimate the heat, moisture and electrical power of the modeled building. ESP-r has three ways to present construction: multi-layer construction (MLC), transparent multi-layer construction (TMC) and complex fenestration construction (CFC). In ESP-r, an opaque wall uses MLC; a clear glazing window uses TMC and a double skin façade with an inner/outer/in-between blind uses CFC. The different calculation of these three constructions is coded in MLC, TMC and CFC source code files respectively. Fig.3.1 shows the abilities of above three construction files. Both TMC and CFC can model solar optics and thermal treatment of a glazed construction. For an ITPVB in-between DSF case, the construction is a transparent shading layer in between two glazing panels. Slat angles can be controlled. Direct and diffuse solar radiation should be extracted and processed differently. More exact, majority of direct solar radiation should be concentrated on solar cell and then part of concentrated radiation transfers to be electricity; majority of diffuse solar radiation should be able to transmit to indoor. The
treatment of glass and shading layers should be different. As it is mentioned in the theoretical model, the conduction and convection by different surface temperature on ITPVB module and cell should not be neglected. All these three constructions are considered being constructed by homogenous layers. The nodal scheme of these three construction file are the same (Fig.3.2). The calculated nodes are only set horizontally. Thus, only horizontal node temperature can be calculated. In one construction, temperature of every node on one surface is equal. Nevertheless, for ITPVB, on the slat surface, the temperature node on cell and module has a big difference. One MLC/TMC/CFC cannot model this phenomenon. The conduction and convection by temperature difference on module and cell cannot be modelled in one construction but two constructions. Table 3.1 shows the ability and limitation of MLC, TMC and CFC for model ITPVB in-between DSF case.

Table 3.1 shows the ability and limitation of MLC, TMC and CFC for model ITPVB in-between DSF case.

---

**Fig.3.1** The abilities of MLC, TMC and CFC files (Lomanowski 2008)

**Fig.3.2** Nodal scheme of MLC, TMC and CFC (Lomanowski 2008)
### Table 3.1 Ability and limitation of MLC, TMC and CFC for model ITPVB in-between DSF

<table>
<thead>
<tr>
<th>Required ITPVB simulation features</th>
<th>MLC</th>
<th>TMC</th>
<th>CFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Able to model transparent construction</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Shading layers</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Angles of blind control (vertical or horizontal)</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exact direct and diffuse radiation for internal solar processing</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exact treatment of between glass slat-type blind.</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculate conduction and convection heat flux with side-by-side constructions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Direct radiation concentrated on solar cell of shading layer and part of it transfer to be electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse radiation transmit the shading layer (module part)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None-homogenous layer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3.4 Simulation model setup

The limitations of standard ESP-r function are the critical parts of modelling ITPVB. The solution is to set up a simple but complete model and adding the needed function by code modification of the existing source code. From the abilities of standard ESP-r, CFC subroutine has the most matching functions. Therefore, setting a model with a modified CFC subroutine is the best way to predict building performance of ITPVB.

**The model**

The simulation model is set as a shoe-box shape room with one window on the south wall. Owing to the module and cell of ITPVB are both homogenous, the convection and conduction by different temperature on module and cell can be calculated with side-by-side constructions. However, ESP-r only allows having maximum six children constructions of one construction. Thus, only six modules can be inserted to the south wall as the window. Each module has one small child construction as cell of ITPVB. Both module and cell constructions apply modified CFC.
function. Fig.3.3 shows the geometry of the test model. Appendix A presents the input of the model.

Fig.3.3 Geometry of the test model

**Code modification**

The construction of ITPVB in-between double skin façade is separated into two CFC constructions: module layer in-between DSF and cell layer in-between DSF. According to the analysis and theoretical study of ITPVB, the module layer only transmits, reflects and absorbs diffuse radiation, and there is no direct radiation involved. On the other hand, the cell layer only absorbs and reflects direct radiation, and there is no diffuse radiation involved. The code modification for these two kinds of CFC construction is based on the theoretical models. In line with theoretical models, the algorithm of long-wave flux and convective flux stays as same as slat-blinds. The equations of functions of ITPVB on building performance are mainly in solar radiation processes.

Fig.3.4 shows the simplified ESP-r solar processing flow including CFC. In original CFC code file, *solar multi-layer subroutine* deals with exact calculation of layers’ radiation reflection, transmission and absorption. On account of similar slat geometry, the modification is overwriting the case of slat-blinds case in *solar multi-layer subroutine*. However, slat-blinds scatter direct radiation to diffuse radiation but ITPVB does not. Therefore, the CFC code file for ITPVB case should set the direct-diffuse radiation fraction as zero. Fig.3.5 shows the modification flow of implementing ITPVB into *solar multi-layer subroutine* in CFC code file. This modified subroutine consists two parts of solar radiation: transmission and absorption. Module and cell layers transmit no direct radiation. Furthermore, in the product concept, the solar cell is very small and invisible because of the high concentration PV. Thus the diffuse radiation should be considered to transmit the actual module size. Nevertheless, in Fig.3.3 the module size is smaller than the actual size because of the occupation of the cell size. So that the module transmits and absorbs less diffuse radiation than the actual product. Concerning about this study concentrating on thermal and electrical performance, the diffuse radiation transmittance and absorptance lose because of the module size can be added into the code by adding an enlarged area ratio $R_a$ ($R_a = \frac{Area_{Module} + Area_{cell}}{Area_{module}}$) with the diffuse radiation transmission in module case. The equations
about absorbed direct radiation are added into the absorption part depending on different layer types.

Fig. 3.4 Simplified ESP-r solar processing flow including CFC (Lomanowski 2008)
3.5 Quality assurance

There is no possibility to do empirical validation for test model of the conceptual product due to no measurement and experiment data. The implementation of ITPVB into dynamic building simulation should be proven if it can be trusted in some extent for further use of simulation. This verification process is called quality assurance. One of the methods to test the quality of implementation is analysis and comparison of some certain results on the object’s physical way. Using other simulation tools can also verify and test the quality of implementation. Furthermore, ESP-r guideline for developers as well gives the tasks of quality assurance for making the correct code modification (Hand 2012). In this study, the quality assurance emphasizes on comparing results with ITPVB’s physical features.

3.5.1 Influence of concentration ratio

However, regarding the difference of real and modelled module and cell geometry, the questions is addressed, which about how close the results to reality is. The geometry of ITPVB’s module and cell presents the concentration ratio. In the conceptual design, the concentration ratio is up to 816. The cell size is micro-sized. They are nearly invisible. In the ESP-r simulation model, the concentration ratio is 20, and the cell size is quite large compared to the real case. The reasons for choosing 20 as the concentration ratio for ESP-r model is that ESP-r cannot model a micro-sized construction, and ESP-r has a limit surface temperature range. A high concentration ratio will leads to a high surface temperature on the cell that exceeds the limited surface temperature range of ESP-r. For high concentration ratio below 100, simulation goes wrong for simulation of the whole year, but it can simulate for just one day in winter. However, the simulated surface temperature of the cell by ESP-r is proven nonsense in Appendix C. Thus, the
surface temperature of ITPVB cannot be used as performance indicator for the building simulation of ITPVB. Notwithstanding, the daily heating loads by different concentration ratios show the very close results when the concentration ratio is beyond 5. Fig. 3.6 shows the simulation results of the daily heating loads with different concentration ratios from 1 to 100 by using modified ESP-r. Fig. 3.7 shows the simulation results of the annual heating and cooling loads with different concentration ratios from 1 to 20. Both daily and annual results show the nearly equal results, which means the concentration ratio does not influent ITPVB’s energy demands and electricity generation when it is larger than 5.

![Fig. 3.6 Hourly space heating load of ITPVB case on different solar cell concentration ratios](image)

![Fig. 3.7 Annual space heating and cooling load and electricity generation of ITPVB case on different concentration ratios](image)
3.5.2 Results of sensitivity case study

Case 1 – Double skin façade (DSF) without shading devices, case 2 – slat-blind in-between DSF, case 3 – high efficient PV panel in-between DSF and case 4 – ITPVB in-between DSF are compared in a sensitivity case study. In case 3 and case 4, the efficiency of solar cell is set as 40%. However, case 3 generate electricity from both direct and diffuse radiation. Case 4 generate electricity just from direct radiation. Solar radiation distribution and energy flow are used as performance indicators for quality assurance. As the assumption, case 1 should transmit most direct and diffuse radiation because of no shading devices. Case 2 should transmit the least diffuse radiation out of case 1 to case 3 because of the opaque shading material. There should be no radiation transmitted in case 3. The amount of absorbed direct radiation transforming to electricity should be as same as case 4. It is because the solar cells in these two cases have the same absorption fraction and efficiency. Then, the space heating and cooling loads can be explained according to solar radiation distribution.

Solar radiation distribution through four cases

Fig. 3.8 illustrates the solar radiation distribution through case 1 to case 4 in a summer sunny day of Amsterdam. Generally, it matches the above assumption. Moreover, case 2 has most direct radiation reflection and case 3 and case 4 has the least. It is because the slat-blind layer in case 2 has a high reflection fraction. Although, comparing to the other cases, case 1 has one less layer. The amount of reflection of case 1 is still more than case 3 and case 4. The reason is that the solar radiation stops at PV layer. There is no reflection at inner glass layer for solar radiation coming from outside. Similar for the diffuse flux, case 2 has most reflection because of the high reflection fraction of slat-blind, and case 3 has least reflection is because of no transmission of PV-blind layer. One less layer in case 1 as well causes the least absorption and most transmission in the fenestration construction. Case 3 and case 4 have more absorption than case 2. However, the absorbed direct flux consists of two usages for case 3 and case 4: for heat gain and electricity generation. Furthermore, the absorption for heat gain in case 3/4 is very close to case 2. It is because the direct radiation absorption fraction of slat-blind layer is 0.5. The direct radiation absorption fraction for heat gain of PV/ITPVB layer should be 0.558 as calculated in equation ①. The reason that although the direct radiation absorption fraction for heat gain of PV/ITPVB layer is higher than slat-blind layer, the absorption in slat-blind is still slightly higher is that case 2 absorbs the more re-reflect flux from shading/PV layer.

\[ a_{PV-Blind/ITPVB} \times (1 - \eta) = 0.93 \times (1 - 0.4) = 0.558 \] ①

Last but not the least, the transmission of diffuse radiation of case 4 is certainly higher than case 2 because of the transparent material and lower than case 1 for one more layer in the fenestration. In case 3, very little direct radiation is also transmitted but formed as diffuse radiation because of the scattering function of slat-blind surface.

Apart from the solar distribution flow in a sunny summer day, the solar distribution flow in a cloudy summer day, a sunny winter day and a cloudy winter day is also tested and presented in Appendix D. Fig. 3.9 concludes the solar distribution through four cases in a different sky type (whether the sky is sunny or not) and seasons. The direct radiation distribution varies by summer and winter but is not influenced by sky type. In winter days, the fenestration has less percentage
of reflection for direct radiation. Except case 1, the rest cases have more percentage on absorption for direct radiation. The percentage of direct radiation for electricity generation of Case 3 and case 4 is also higher in winter. However, the season and sky type do not influence the solar diffuse radiation distribution.
Fig.3.8 solar radiation flow through Case 1 - Double skin façade (DSF) without shading devices, case 2 – slat-blind in-between DSF, case 3 – high efficient PV panel in-between DSF and case 4 - ITPVB in-between DSF (red ray presents the direct solar flux, orange ray presents the diffuse solar flux, green ray presents solar flux using for electricity generation and blue box presents the building components in case 1 to case 4)

<table>
<thead>
<tr>
<th>Direct radiation distribution through fenestrations in summer days</th>
<th>Direct radiation distribution though fenestrations in winter days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CASE 1</strong></td>
<td><strong>CASE 2</strong></td>
</tr>
<tr>
<td>Transmission</td>
<td>30%</td>
</tr>
<tr>
<td>Absorption</td>
<td>40%</td>
</tr>
<tr>
<td>Reflection</td>
<td>24%</td>
</tr>
<tr>
<td>Electricity</td>
<td>24%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diffuse radiation distribution though fenestrations in both summer and winter days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CASE 1</strong></td>
</tr>
<tr>
<td>Transmission</td>
</tr>
<tr>
<td>Absorption</td>
</tr>
<tr>
<td>Reflection</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
</tbody>
</table>

Fig.3.9 Direct solar radiation distribution through four fenestrations in summer days (a) and winter days (b); diffuse solar radiation distribution through four fenestrations in both summer and winter days (c).

**Energy demands**

If taking the inside shading/PV layer as homogenous layer, the heat fluxes influence indoor heat gain according to Fig.2.2b is transmitted solar flux and absorbed flux converting to heat gain (convective and long-wave flux). However, transmitted flux has more influence on indoor heat gain from solar radiation. It is because the convective and long-wave fluxes have two directions: from the fenestration to indoor and from the fenestration to outdoor. In another words, not all of
absorbed flux devotes to indoor heat gain. Therefore, the assumption of indoor heat gain speculating from solar radiation distribution (Fig.3.9) should be case 1 > case2/case4 > case 3. The comparison of indoor heat gain of case 2 and case 4 is hard to assume because case 2 has more percentage of transmitted and absorbed flux converting to heat gain for direct radiation, but equal percentage for diffuse radiation. Furthermore, case 4 has more percentage of transmitted diffuse flux and case 2 has more percentage of transmitted direct flux. Thus, the comparison of indoor heat gain of case 2 and case4 should depend on the direct and diffuse radiation fraction. Depending on the assumption of indoor heat gain comparison, space cooling load should have the same rank and on the contrary, space heating load should have the opposite rank.

Fig.3.10 shows the simulation results of space heating and cooling loads of four cases using Amsterdam’s weather file. The same as the assumption, Case 1 has the least space heating load and most space cooling load, and case 3 is to the contrary. It as well illustrates that case 4 has lower space heating and cooling loads than case 2.

As the solar distribution through four different fenestration constructions has been explained equivalently by the physical processes and the simulated results match the assumption based on the physical features, the simulated thermal behavior and electricity generation can be trusted in an acceptable extent. Therefore, the implementation can be used for a whole building’s simulation.
4. Building simulation of ITPVB

After the quality of the implementation of ITPVB into dynamic simulation is assured, a whole building’s simulation can be used for investigation of influences by buildings’ physics and climate. Referring from the market focus of one developing ITPVB product: SolarSwing Energy, the building simulation focuses on commercial buildings. Building performance influences by climate, building’s orientation, construction’s thermal mass and building’s fenestration with shading coverage are discussed with simulated results. Comparison with double skin facade without shading devices and slat-blind in-between double skin façade discovers how much potential ITPVB in-between double skin façade contains comparing with conventional façades of commercial buildings.

4.1 Method

The method of building simulation is to simulate a simplified geometry model with equivalent HVAC control and scheduled casual heat gain profile by using the implemented ESP-r. The results about building performance are presented in three points of view:

- Energy demand/generation and thermal comfort;
- Energy saving on heating and cooling demand compared to double skin facade without any shading devices;
- If the building can be Zero Energy Building (ZEB) when the thermal comfort is satisfied.

Considering about the above three points expressed by performance indicators, how much influence by climate, building’s orientation, construction’s thermal mass and building’s fenestration with ITPVB coverage can be figured out. Apart from the climate cases, all other cases use Amsterdam weather file; apart from the orientation cases, all other cases have window installed with slat-blind/ITPVB on the south façade.

4.1.1 Performance indicator

For building performance simulation, the performance indicators expressed in values is used to assess how well the building behaves on energy, health, indoor air quality and thermal comfort. For different aspects of building performance, each aspect has various indicators, for example, energy can be showed in annual primary/secondary energy demand; thermal comfort can be evaluated by Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) or overheating hours. For a certain type of building, the building regulations in different countries may also use the different indicators to restrict the acceptable range for the aspects of building performance. For instance, the requirement from ASHRAE Standard 55-2010 states that PPD should be lower or equal 20% and a recommended PMV limit is -0.5<PMV<0.5.

In this research, the focus is on energy demand, renewable energy generation and thermal comfort. For energy demand, space heating and cooling loads are used as the import indicators to differ the thermal behaviors of DSF, DSF with in-between blind and DSF with in-between ITPVB. The electricity output from photovoltaic can present ITPVB’s electricity generation ability. For an overall point of view about energy demand and renewable energy generation, primary energy
indicator EP\textsubscript{r} (Kurnitski 2013) is used to assess if the building can be a Zero Energy Building (ZEB). Moreover, PMV/PPD is used to do the assessment about thermal comfort so that the result can meet the most used requirement from ASHRAE. Furthermore, ASHRAE has a specific standard effective temperature (SET\textsuperscript{\textdegree}) to combine using with PMV for present a more accurate occupants’ feeling to thermal environment. Thus, in this research, a SET\textsuperscript{\textdegree} combined PMV is used instead of commonly used PMV.

Space heating and cooling can be approached directly from ESP.\textsubscript{r}. Thermal comfort indicator PPD/PMV has the different setting for clothing level in summer and winter. In the summer, a short sleeves shirt and trousers are considered. In the winter, a pair of suit is considered. The hottest and coldest day is used to stand for the people’s satisfaction and feeling for thermal comfort. The primary energy indicator for different heating and cooling systems are calculated following with the method from (Kurnitski 2013).

### 4.1.2 Model set up

In this building simulation section, a 13.5m\textsuperscript{2} office room with a 5.32m\textsuperscript{2} window on the south façade is used as the geometry model for simulation. Instead of simulating a whole building, simulating one standard office room can reduce much simulation time and decrease the complexity of the model. Although in this section, the results are not from a whole-building simulation. The standard office as well has the every essential element as it from a whole building. The standard office has a scheduled control of heating and cooling set-points, lighting and equipment. The office has scheduled occupancy due to the scheduled working hours. The HVAC control, casual gain and other input information are listed in Appendix A. The standard office building can be roughly counted as numbers of the standard office. Fig.4.1 shows the geometry of the standard office use for DSF and slat-blind in-between DSF (a) and ITPVB in-between DSF (b).

![Geometry of Standard Office](image)

**Fig.4.1** The geometry of the standard office use for DSF and slat-blind in-between DSF (a) and ITPVB in-between DSF (b)

### 4.2 Influence by climate type

Four locations are chosen as four different climate types: Amsterdam, Warsaw, Madrid and Abu Dhabi. Amsterdam and Warsaw are medium climates, which has both hot and cold days through a year and close direct and diffuse solar radiation. Heating degree day (HDD) and cooling degree
day (CDD) is used to reflect energy demand on heating/cooling. HDD is defined the temperature difference when outside temperature is lower than the base temperature when turning heating on. It is similar for CDD (Web-3). In Fig. 4.2, Warsaw has larger HDD range through a year. Madrid and Abu Dhabi stands for hot climates. Abu Dhabi has an extreme case with the desert climate. Referring to the CDD measurement in fig 4.2b, Abu Dhabi has much more cooling needs than other locations. Furthermore, according to the climate research in chapter 2, those four locations have various amounts of direct radiation and close diffuse radiation.

![Fig.4.2 Monthly-summed (a) heating degree day and (b) cooling degree day in four cities in 2013](image)

As the results of spacing heating and cooling loads and electricity generation shown in Fig.4.3(a) an office room installed with ITPVB in Abu Dhabi generates the highest electricity and has the highest cooling load and no heating load. However, its electricity generation is just slightly higher than the case of Madrid. On the other hand, the space cooling load of Madrid case is about a half less. On the other side, Amsterdam and Warsaw has close latitude and diffuse and direct radiation but different yearly temperature range. However, the heating and cooling system in this model is zone temperature controlled. Thus, Amsterdam and Warsaw also has a big difference on space heating and cooling loads but little disparity on electricity generation. In Fig.4.3(b), comparing with DSF without shading devices, ITPVB and slat-blind case saves more percentage of energy on heating and cooling in a colder climate case than the hot climate case. Meanwhile, ITPVB also saves a bit more percentage (within 9%) energy than slat blind. Furthermore, the hot climate has more potential to save cooling load comparing to slat blind. To the contrary, the saving percentage for heating load shows the opposite trend except Abu Dhabi. Nevertheless, even the Madrid case shows a large percentage increase of heating load comparing to DSF and slat-blind case, and the amount increase is still small because of the small amount of heating load.
4.3 Influence by building's orientation

Fig.4.4(a)(b) shows the energy demand/generation and savings. Being different from that the climate influences more on space heating and cooling loads, the building’s orientation influences more on electricity generation. It can be seen in Fig.4.4(a), ITPVB on the south façade has much more electricity generation than the north case, but the heating demands are within a small difference. Fig.4.4(b) shows that ITPVB installed on south façade has the most potential to save energy. The south case is also the only one case which saves more energy on cooling than slat-blind. For heating, except the North case, all other simulated orientation has a slight increase (within 11%). The reason is that the North façade only receive very little direct radiation. Thus, the more solar radiation absorption store the heat in ITPVB component, and it keeps the façade warm longer than DSF.
Influence by construction’s thermal mass

Thermal mass describes the heat storage ability of the construction. A heavy-weight thermal mass construction can store more heat. The outside environment has less influence with heavy-weight constructions. A heavy-weight thermal mass construction has high specific heat capacity and high density. For the investigation the influence by construction’s thermal mass for ITPVB, concrete and timber are used for all walls as heavy-weight and light-weight thermal mass cases to compare.

Fig.4.5 (a) illustrates that the choice of thermal mass does not have many influences on both electricity generation and space cooling load. Two cases generate the same amount of electricity because of the same climate and window area. It has a more obvious impact on the space heating load. The choice of thermal mass also does not have an influence on energy saving on cooling of ITPVB case comparing to DSF, but energy saving on cooling of slat-blind case. A building with heavy-weight thermal mass construction and ITPVB has more ability to save energy using for cooling than the building with conventional slat-blind and the same construction. It also has better performance on increased heating load.

Fig.4.5 ITPVB in-between double skin façade’s (a) Space heating and cooling loads and electricity generation; (b) Space heating and cooling loads saving comparing with slat-blind in-between DSF based on DSF without any shading devices when an office room faces to different orientations.

Influence by building’s fenestration with ITPVB coverage on the south façade

A fully glazed façade is very common in today’s commercial building. For the analysis of feasibility for applying ITPVB on different glass coverage of façade, the base case (Fig.4.1) with 59% coverage and a fully glazing façade (100% coverage, Fig.4.6) is compared.
Fig.4 100% coverage case for (a) slat-blind in-between DSF and DSF and (b) ITPVB in-between DSF.

In Fig.4.7(a)(b), with more glazed area, 100% coverage case has more electricity generation and spacing heating and cooling loads. With the coverage increasing 41%, only electricity generation follows the same increase percentage. Space heating and cooling loads only increase 30% and 35% respectively. However, ITPVB in 100% coverage case has more space cooling loads saving percentage. ITPVB also has larger potential to save cooling load than slat-blind. In the winter, the heating load from ITPVB with 100% coverage case also has the least heating load increase.

Fig.4.7 (a) ITPVB’s in-between double skin façade’s (a) Space heating and cooling loads and electricity generation; (b) Space heating and cooling loads saving comparing with slat-blind in-between DSF based on DSF without any shading devices when an office room has different ITPVB coverage on one façade.

4.6 Thermal comfort

The thermal comfort evaluation uses PMV/PPD as the performance indicator in this research. PMV that indicates the occupants’ feelings about warm and cold level depends on six parameters: occupants’ metabolism and activity level, clothing level, relative humidity, air flow velocity, air temperature and mean radiant temperature. The mean radiant temperature depends on the inside surface temperature of the façade. However, it has been proven in Appendix C that surface temperature of solar cell on ITPVB is not trustful. Thus, it would influence the accuracy of PMV simulation results. Fig.4.8 (a)-(d) shows PMV/PPD results by using the simulated surface
temperate. By comparing with the PMV with slat-blind case, the PMV/PPD can indicate the thermal comfort of ITPVB applied building on some extent. In the most of the tested cases, slat-blind has a slightly higher PMV than ITPVB cases, which means occupants in slat-blind cases feel warmer than occupants in ITPVB cases. However, the simulated surface temperature of solar cell in ITPVB cases would be very high (up to 300°C) as tested in Appendix C. Furthermore, the module’s surface temperature is lower than the slat-blind’s. Therefore, it means the effect that people feel slight warmer in slat-blind cases is mainly because a lower surface temperature of the module. Thus, it indicates the module’s surface temperature has more influences than the inaccurate simulated cell’s surface temperature. As the simulated module’s surface temperature is more trustful than the cell’s, the PMV and PPD can still be trusted at a big extent for a rough primary evaluation.

Apart from Abu Dhabi case, the rest cases are somehow in the recommended limit for PMV. In Abu Dhabi case, the whole range of PMV in summer and winter is close to 1. PMV equals 1 means slightly warm. Thus, majority of people still feel satisfied, which is shown in PPD graphics, except the last working hour in summer and first and last working hour in winter, at least 80% people are satisfied with the indoor environment. The complaint more than 20% in other cases are all about feeling slightly cold/warm at the first working hour and last working hour.

In addition to south case in the summer, in all other cases, slat-blind case gives people a slightly cold indoor environment. However, the south case is as well the exception case that is not mostly within the PMV limit. On the other hand, all four orientation cases show a very close result for PMV in winter. In thermal mass cases, the result of slat-blind and ITPVB is very close, which means the thermal comfort results have very small influence on thermal comfort for the indoor environment. The thermal comfort in both lightweight and heavyweight case is acceptable. For thermal comfort in ITPVB/slat-blind coverage cases, occupant may feel a little bit warm in 59% coverage case since 12:30 in summer. The satisfaction is still acceptable. On the contrary, occupants feel warm in 100% coverage case in winter. Slat-blind in 100% coverage case has more than 20% complaints at 8:30 and 13:30 to 15:30. Comparing to slat-blind, ITPVB has a better feedback, although people feel slightly warm in winter from 12:30 to 16:30, this increased warm environment does not make the PPD over 20%.

Over all the cases, the complaint about feeling slightly cold in ITPVB case in the morning is mainly because very little direct radiation. Much complaints happening in the last working hour is because HVAC system turns off at 18:00.
Fig.4.8 (a) Thermal comfort in summer and winter of ITPVB/slat-blind in-between double skin façade when an office room is at different locations (blue area is the recommended limit)
Fig. 4.8 (b) Thermal comfort in summer and winter of ITPVB/slat-blind in-between double skin façade when an office room face to different orientations (blue area is the recommended limit).

Fig. 4.8 (c) Thermal comfort in summer and winter of ITPVB/slat-blind in-between double skin façade when an office room has different thermal mass constructions (blue area is the recommended limit).
4.7 Energy consumption and generation reflecting on the possibility to be ZEB

Different systems for heating and cooling are assigned the simulation model: boiler and chiller, high efficient heat pump (COP=4.0) and medium efficient heat pump (COP=2.5). Apart from boiler using gas, the rest systems use electricity. It is assumed the electricity for lighting and equipment in the office is 100W/m². Then, the energy consumption and generation can be converted to primary energy. A primary energy indicator EP_p is calculated to evaluate if the building can be zero energy building. If EP_p is lower than 0, the building can be ZEB. After testing all the case including ITPVB in-between DSF with different climate, building’s orientation, construction’s thermal mass and ITPVB’s coverage, eight cases can be ZEB. Only EP_p of cases about ITPVB with 59% coverage of west and north façade in Amsterdam is higher than 0 according to Fig.4.9. Appendix E shows the spreadsheet of the EPP calculation for all ITPVB cases.

In these two cases which cannot be ZEB, it is assumed that they would have the electricity support from the grid. Thus, the renewable energy ratio is used to illustrate how the breakdown of the renewable energy usage in these buildings is. Fig. 4.10 shows that the building using ITPVB on the west façade in Amsterdam has a renewable energy ratio around 69% to 79% by the different heating and cooling system. A high efficient heat pump has 10% more renewable energy coverage than a heating and cooling system by using boilers and chillers. On the other hand, a building applying ITPVB only on north façade in Amsterdam can only have less than 40% renewable energy coverage. Even using a high efficient system, the building still need a larger amount of electricity support from the grid.

Fig.4.9 shows the result of all ZEB cases’ EP_p. The minus value means except supply the building, how much generated electricity is available to use. From the calculation, Madrid case has the most renewable electricity generation left to use. Over the three heating and cooling system, high efficient heat pump has the most potential to save more primary energy. However, the different of three different systems is not large. In these two non-ZEB cases, the largest share of the electricity use is for support the lighting, office equipment and building electrical facilities. Nevertheless, cooling system has the smallest share because of the high efficiency and low demands. Using boilers as heating system has the lowest efficiency comparing to heat pump. Thus, it has a higher share of primary energy need. However, the primary indicator and renewable energy ratio is calculated based on an annual level. Therefore, it has not yet considered about the hourly situation that the low renewable energy generation and high heating/cooling demand. Nevertheless, according to (Marszal et al. 2011), currently using annual total result is commonly used for defining if a building is a zero energy building. Thus, ITPVB can be considered has a large potential to lead the building to be zero energy building in many situations.
Fig. 4.9 Primary energy indicator ($EP_P$) of all ITPVB cases (AMS: Amsterdam, MAD: Madrid, WAW: Warsaw, ABU: Abu Dhabi, E: east, S: south, W: west, N: north, 59%: 59% coverage, 100%: 100% coverage, LW: light-weight, HW: heavy-weight)

Fig. 4.10 Renewable energy ratio ($RER_P$) of the cases which cannot make zero energy building
5. Conclusion

5.1 Concluding Remarks

This research has analyzed the potential of ITPVB on energy saving and leading the buildings to become zero energy building in different situations. This research created a virtual testbed for evaluating building performance of the innovative building element on aspects of thermal and electrical behavior. This testbed creates the opportunities to assess the potential of ITPVB using various materials properties. Thus, it helps the developer of ITPVB to make decisions on material choice and improvement. The implementation procedure gives insights for evaluating building performance of other innovative building elements on the product’s designing phase. The core of the methodology to evaluate innovative building elements can be concluded as: knowing the “behind story” and theory and modifying “on the shoulders of giants” to fit the case. This research has ensured the quality of the simulation by explaining the simulated results of the component with its physical processes. The demonstrated solar radiation flow through ITPVB in-between double skin façade shows the promising use-for-electricity-generation direct radiation and enter-room-for-daylight diffuse radiation. Moreover, ITPVB has a large potential to achieve saving around 50% of space cooling load according to the building simulation comparing with the building without shading. Compared to conventional shading devices, such as slat-blinds, ITPVB are quite competitive on energy saving, thermal comfort and electricity generation aspect’s potential. On account of the on-site electricity production, ITPVB as one of the new high-tech configuration of building façade can guide a large amount of double skin façade buildings in EU to achieve the target about being energy nurture by the year 2020.

5.2 Future work

By obtaining the features of ITPVB, limitation of the testbed and pro and cons of ITPVB from the simulation results, the future work is recommended in two directions: further simulation research and market/product’s development focuses.

This research focuses on the thermal and electricity part of the building performance of ITPVB. However, one of the biggest features of ITPVB which is optical performance has not yet been predicted. From the analysis of ITPVB, it is transparent and can optically transmit the diffuse flux. Thus, it could bring more daylight to indoor. This feature has a big influence to the building: the decrease artificial lighting use. Less artificial lighting also reduces the casual heat gain from lighting. Form the testbed simulation, ITPVB in-between double skin façade can transmit 37% diffuse radiation. This finding can be a reference and help to modify the illuminance enter from the fenestration. Thus, the future work for this product can be developing an optical model with simulated diffuse radiation transmittance and using a dimming system based on the sensor of entered diffuse radiation from the optical model. Then the optical model combines with the implemented model in this research to figure out energy saving for an ideal building for ITPVB referring the thermal effect of daylight controlled lighting [Clarke and Janak 1998](Reinhart and Herkel 2000). On the other hand, the implemented model has a big difference with the
conceptual product at the solar cell size. Although, it has been proven the cell size has a very small influence on energy demands. Although the surface temperature cannot be modelled in this research, it is still important for product development and thermal comfort evaluation. Thus, the improvement of the implemented model at surface temperature is also interesting and important for future work. Lastly, in this research, it is assumed the double skin façade is closed. Thus, with the influence of airflow in the double skin façade, the convection and conduction flux would be changed. The airflow would also influence the surface temperature. As a more complex and realistic case, the research of investigating the building performance by the influence of airflow in double skin façade would also be helpful and challenging.

On the market point of view, ITPVB has large potential on saving space cooling load comparing to conventional shading devices. Furthermore, the theoretical electricity generation is also higher than conventional BIPV. Thus, the market focus of this kind of product should be the double skin façade buildings with south/east orientation located in hot climate zone. Moreover, for better energy saving, applying ITPVB to a fully glazed façade with other constructions choosing heavyweight on thermal mass on the above condition of the building, can express the biggest potential of ITPVB. If there is a building with all the optimized condition, this building can be a promising example project to attract the attention of public and potential customers. On the product’s development viewpoint, an intelligent control system can help balancing the excessive space heating load (compared with no shading situation) and small amount of electricity generation in cold hours in winter. The intelligent control can involve with sensors for solar radiation and outdoor temperature. In the morning or cloudy day of winter, the system can be shut down. Furthermore, combining with the market focus, if the investor wants a worldwide market, for example, even hoping a good feasibility in cold climate country, producing multi-types of ITPVB with different function or control strategy focus would be a choice. For cold climate countries, the development focus should be CPV efficiency and quick respond control system. For extremely hot climate countries, the developers can think of a method to harvest the thermal energy that is released from absorption in the CPV modules in a useful way. On the other hand, because the simulation of CPV only considered about the solar cell efficiency but not combination with system efficiency, the simulated result of electricity generation must be higher than a real case. However, on this developing phase, the configuration of CPV has not been confirmed. Thus, a recommendation future work is investigating an optimized CPV configuration by using the simulation of the testbed to find out the influence on building performance. Similarly, the current or updated testbed can always help to figure out if any design decision is effective to better building performance or not.
Acknowledgement

The author would like thank the following persons for their support: prof.dr.ir. Jan Hensen for suggestions of the big map and professional advices on research methodology, ir. Roel Loonen for support of model development and daily supervision, and ir. Sam Kin for ITPVB’s product information support. Last but not the least, the author would like to thank Eindhoven University of Technology and SolarSwing® for academic and technic support.
Reference


Web-2 http://www.solarswing.com/

Web-3 http://www.solarswing.com/
Appendix A: Input for models

1. Input for implementation model

1.1 Climate file
- Climate: Amsterdam

1.2 Geometry
- Room L x W x H: 5.4m x 3.6m x 2.7m
- Window L x H: 4.2m x 2m
- From ground to the lowest edge of the window: 0.5m
- From left south wall edge to left window edge: 0.5m
- Module(w1-w6) L x H: 1.4m x 1m
- Cell (c1-c6) is 5% of Module locates in the center of module

1.3 Construction
All the construction materials can be found in ESP-r default database.
- External walls, ceiling and floor (MLC):

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thick (mm)</th>
<th>Name of material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>Light brown brick</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>Glass wool</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>Air gap</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>Breeze block</td>
</tr>
</tbody>
</table>
• ITPVB Case/slat-blind case – module/cell/slat-blind (CFC)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thick (mm)</th>
<th>Name of material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>CLEAR_6.DAT</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>air</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>VB 1/2 IN med Al/RLD sunblock/VB 1/2 med Al</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>air</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>CLEAR_6.DAT</td>
</tr>
</tbody>
</table>

• DSF case (TMC)

<table>
<thead>
<tr>
<th>Layer</th>
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<th>Name of material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>55</td>
<td>Air</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>LoE Clear 6mm</td>
</tr>
</tbody>
</table>

1.4 CFC profile
CFC profile can be modified in xxx.cfc file.
• Glass/module transmission and reflection: 0.771 and 0.07;
• Cell transmission and reflection: 0.0 and 0.07;
• Slat-blind transmission and reflection: 0.0 and 0.5
• Glass/module/cell long-wave transmission and emission: 0.0 and 0.84
• Slat-blind long-wave transmission and emission: 0.0 and 0.84
• Angle control for module/slat-blind: 45° horizontal

1.5 Control profile
• Basic control: always on
• Heating set-point: 20° C
• Cooling set-point: 24° C

1.6 Air flow
• No Air flow

1.7 Casual gain
• No casual gain
2. **Input for building simulation model**

The building simulation mode refers to the base case model in technique features of ESP-r exemplar database. However, the corridor and once office is moved for the reduction of complexity and influence by heat transfer from the neighbor.

![Diagram of building simulation model](image)

### 2.1 Climate file

- Climate
  - Influence case: Climate file
  - Climate: Amsterdam/Warsaw/Madrid/Abu Dhabi
  - Orientation: Amsterdam
  - Thermal mass: Amsterdam
  - Coverage: Amsterdam

### 2.2 Geometry

- Room L x W x H: 4.5m x 3m x 3m
- Window L x H: 2.8m x 1.9m
- From the highest edge of spandrel to the lowest edge of the window: 0.05m
- From left south wall edge to left window edge: 0.1m
- Module(w1-w6) L x H: 0.9333m x 0.95m
- Cell (c1-c6) is 5% of Module locates in the center of module
2.3 **Construction**

- Internal wall (include pt_general, pt_other, ptn_corid, ptn_other_a, ptn_other_b):

<table>
<thead>
<tr>
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<th>Thick (mm)</th>
<th>Name of material</th>
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<tbody>
<tr>
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<td></td>
<td>White gypboard</td>
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<tr>
<td>1</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>Air gap</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>White gypboard</td>
</tr>
<tr>
<td>Thermal mass: light-weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>OSB wood</td>
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</table>

- Thermal mass: heavy-weight

<table>
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<tbody>
<tr>
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<td>Concrete 150mm</td>
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</tbody>
</table>

- Non-glazing façade part (spandrel): insul_frame (MLC)

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<td></td>
<td>Grey cotd alum</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>Glass fibre quilt</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Grey cotd alum</td>
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<tr>
<td>Thermal mass: light-weight</td>
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</tr>
<tr>
<td>1</td>
<td>74</td>
<td>OSB wood</td>
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</table>

- Thermal mass: heavy-weight

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<tbody>
<tr>
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<td>74</td>
<td>Concrete 150mm</td>
</tr>
</tbody>
</table>

- Floor: susp_flr_re (MLC)

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<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>Heavy mix concrete</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>Air gap</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>Chipboard</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Wilton</td>
</tr>
</tbody>
</table>

- Ceiling (MLC)

<table>
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<tr>
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</thead>
<tbody>
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<td>Glasswool</td>
</tr>
<tr>
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<td>100</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>Ceiling material</td>
</tr>
</tbody>
</table>

- Window frame (include part_frame, frame): insul_frame (MLC)

<table>
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<tbody>
<tr>
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<tr>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>Glass fibre quilt</td>
</tr>
<tr>
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<td>4</td>
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</table>
### Internal Window (part_glaz): dbl_glz (TMC)

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</thead>
<tbody>
<tr>
<td>Climate/orientation/ thermal mass/coverage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>Plate glass</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>Air gap</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>Plate glass</td>
</tr>
</tbody>
</table>

### Door (MLC)

<table>
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</tr>
<tr>
<td>1</td>
<td>25</td>
<td>oak</td>
</tr>
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### External window: ITPVB Case/slat-blind case – module/cell/slat-blind (CFC)

<table>
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<tbody>
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<td>Climate/orientation/ thermal mass/coverage</td>
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<tr>
<td>1</td>
<td>6</td>
<td>CLEAR_6.DAT</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>air</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>VB 1/2 IN med Al/RLD sunblock/VB 1/2 IN med Al</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>air</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>CLEAR_6.DAT</td>
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</tbody>
</table>

### External window: DSF case (TMC)

<table>
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<tbody>
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<td>Climate/orientation/ thermal mass/coverage</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>LoE Clear 6mm</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>Air</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>LoE Clear 6mm</td>
</tr>
</tbody>
</table>

### 2.4 CFC profile

- Glass/module transmission and reflection: 0.771 and 0.07;
- Cell transmission and reflection: 0.0 and 0.07;
- Slat-blind transmission and reflection: 0.0 and 0.5
- Glass/module/cell long-wave transmission and emission: 0.0 and 0.84
- Slat-blind long-wave transmission and emission: 0.0 and 0.84
- Angle control for module/slat-blind: 45° horizontal

### 2.5 Control profile

**Basic control**

<table>
<thead>
<tr>
<th>Day type</th>
<th>Period</th>
<th>Heating set-point (° C)</th>
<th>Cooling set-point (° C)</th>
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</thead>
<tbody>
<tr>
<td>Weekdays</td>
<td>18:00-6:00</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>6:00-18:00</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Saturday</td>
<td>0:00-9:00</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>9:00-17:00</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>17:00-24:00</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Sunday</td>
<td>0:00-9:00</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>
2.6 Air flow

<table>
<thead>
<tr>
<th>Day type</th>
<th>Infiltration (ACH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekdays, Saturday</td>
<td>0.5</td>
</tr>
<tr>
<td>Sunday</td>
<td>0.33</td>
</tr>
</tbody>
</table>

2.7 Casual gain

[Graph showing casual gains for different days and times.]
Appendix B: Modified Subroutine

The implementation modified (codes in red) the subroutine solar_multilayer of CFC_thermal_and_aux.F is as followed:

```fortran
C ********************************************************************
C --solar_multilayer--
C
C Calculates reflected, transmitted and absorbed solar fluxes for a glazing/shading multilayer system. A solar flux balance is established for each layer, including beam-beam fluxes, beam-diffuse fluxes due to scattering shading layers, and diffuse-diffuse fluxes.
C
C Details in:
C
C INPUT:
C GBM - External beam solar irradiance [W/m²]
C GDF - External diffuse solar irradiance [W/m²]
C IBM - Internal beam solar irradiance [W/m²]
C IDF - Internal diffuse solar irradiance [W/m²]
C PVe – PV efficiency
C Rc – Concentration ratio
C Ra – Area ratio
C
C OUTPUT:
C TRANSBB_SYS - Total transmitted beam solar flux [W/m²]
C TRANSDD_SYS - Total transmitted diffuse solar flux [W/m²]
C REFL_SYS - Total reflected solar flux (beam+diffuse) [W/m²]
C AbsSol - Absorbed solar flux at each layer [W/m²]
C
C ********************************************************************

subroutine solar_multilayer(icalc_mode, icomp, isurf, icfctp,
&     GBM, GDF, IBM, IDF,
&     TRANSBB_SYS, TRANSDD_SYS, REFL_SYS, AbsSol)

IMPLICIT NONE
#include “building.h”
#include “CFC_common.h”

INTEGER LayNo, n, m, i, icomp, isurf, icfctp, icalc_mode
INTEGER itype
```
REAL GBM, GDF, IDF, IBM, PVout, Acell, Amodule, PVoutsum
REAL TRANSBB_SYS, TRANSBD_SYS, TRANSDD_SYS, REFL_SYS
REAL AbsSol, PVe, Rc, Ra
REAL rfdd, rbdd, tfdd, tbdd
REAL rfbd, rbbd, tfbd, tbbd
REAL rfbb, rbbb, tfbb, tbbb
REAL BB, BD, DD, D, SS, SSB, SSD
REAL Bminus, Bplus
REAL Dminus, Dplus
REAL ae, ap, aw, bp

INTEGER xx

DIMENSION rfdd(me), rbdd(me), tfdd(me), tbdd(me) ! SW Layer Properties
DIMENSION rfbd(me), rbbd(me), tfbd(me), tbbd(me) ! SW Layer Properties
DIMENSION rfbb(me), rbbb(me), tfbb(me), tbbb(me) ! SW Layer Properties
DIMENSION BB(me*2+2), BD(me*2+2), DD(me*2+2), D(me*2+2), SS(me)
DIMENSION AbsSol(me), SSB(me), SSD(me)
DIMENSION Bminus(me*2+2), Bplus(me*2+2)
DIMENSION Dminus(me*2+2), Dplus(me*2+2)
DIMENSION ae(me*2+2), ap(me*2+2), aw(me*2+2), bp(me*2+2)

LayNo = ncfc_el(icomp, icfctp)
Acell = 1
Amodule = 20
Rc = Amodule/Acell
Ra = Amodule/(Amodule-Acell)
PVe = 0.4

C Assign optical properties for each layer from commons to temp arrays
DO 10 i=1, LayNo
  rfbb(i) = SolRFbb(icomp, isurf, icfctp, i)
  rbbb(i) = SolRBBb(icomp, isurf, icfctp, i)
  tfbb(i) = SolTFbb(icomp, isurf, icfctp, i)
  tbbb(i) = SolTBBb(icomp, isurf, icfctp, i)
  rfbd(i) = SolRFbd(icomp, isurf, icfctp, i)
  rbbd(i) = SolRBbd(icomp, isurf, icfctp, i)
  tfbd(i) = SolTFbd(icomp, isurf, icfctp, i)
  tbbd(i) = SolTBbd(icomp, isurf, icfctp, i)
  itype = icfcltp(icomp, icfctp, i)

C........ Set sky and ground diffuse properties for slat blinds, if requested
IF (itype.eq.2 .AND. icalc_mode.eq.i_sky) THEN
rfdd(i)=SolRFskydd(icomp,isurf,icfctp,i) 
brdd(i)=SolRBskydd(icomp,isurf,icfctp,i) 
tfdd(i)=SolTFskydd(icomp,isurf,icfctp,i) 
tbdd(i)=SolTBskydd(icomp,isurf,icfctp,i)
else if (itype.eq.2.and.icalc_mode.eq.i_ground) then
rfdd(i)=SolRFgrddd(icomp,isurf,icfctp,i) 
brdd(i)=SolRBgrddd(icomp,isurf,icfctp,i) 
tfdd(i)=SolTFgrddd(icomp,isurf,icfctp,i) 
tbdd(i)=SolTBgrddd(icomp,isurf,icfctp,i)
else
rfdd(i)=SolRFdd(icomp,isurf,icfctp,i) 
brdd(i)=SolRBdd(icomp,isurf,icfctp,i) 
tfdd(i)=SolTFdd(icomp,isurf,icfctp,i) 
tbdd(i)=SolTBdd(icomp,isurf,icfctp,i)
end if

10 continue

!MULTILAYER CALCULATION
n=LayNo+2
m=2*n-4
!Beam fluxes
CALL SETCoef(tbbb,tfbb,rbbb,rfbb,GBM,n,aw,ap,ae,bp)
! back beam source...used for interior insolation distribution
bp(1)=-IBM
CALL TDMAsol (ae,ap,aw,bp,n,BB)
BB (m+1)=rfbb (1)*GBM+tbbb (1)*BB (m)
!Diffuse-beam fluxes
CALL SETCoef(tbdd,tfdd,rbdd,rfdd,GBM,n,aw,ap,ae,bp)
!Set direct-diffuse fraction as zero
IFT (icfcltp(icomp,icfctp,3).eq.iVenBlind .or.
& icfcltp(icomp,icfctp,3).eq.iRollerBlind)THEN
  tbbd=0.0
  tfbd=0.0
  rbbd=0.0
  rfbd=0.0
ENDIF
bp(1)=-0.00001*BB(1)
bp (2)=-(rbbd (n-2)*BB (2)+tfbd (n-2)*BB (3))
DO  i=2,n-2,1
  xx=2*i-1
  bp (xx)=-(rfbd(n-i)*BB(2*i-1)+tbbd(n-i)*BB(2*i-2))
  xx=2*i
  bp (xx)=-(rbbd(n-i-1)*BB(2*i)+tfbd(n-i-1)*BB(2*i+1))
ENDDO
i=n-2
xx=2*i
ae(xx)=0.
bp(xx)=-(rbd(1)*bb(2*i)+tfd(1)*(GBM))
i=n-1
xx=2*i-1
bp(xx)=-((rbd(1))*(GBM)+(tbd(1))*(bb(2*i-2)))
CALL TDMASol(ae, ap, aw, bp, n, BD)
BD(m+1)=rfd(1)*GBM+tbd(1)*bb(m)+tbd(1)*BD(m)

!Diffuse fluxes
CALL SETCoef(tbdd, tfdd, rbd, rfd, GDF, n, aw, ap, ae, bp)
bp(1)=-IDF
CALL TDMASol(ae, ap, aw, bp, n, DD)
DD(m+1)=rfd(1)*GBD+tbd(1)*DD(m)
DO i=1, m, 1
D(i)=DD(i)+BD(i)
ENDDO
D(m+1)=DD(m+1)+BD(m+1)

!Transmittance and Reflectance Calculation
IF (icfcltp(icomp, icfctp, 3) .eq. iVenBlind) then
TRANSBB_SYS = 0.0! /GBM, if layer is module, no direct radiation is transmitted
TRANSBD_SYS = BD(1)! /GBM
TRANSDD_SYS = Ra*DD(1)! /GDF, Enlarge transmitted diffuse radiation
TRANS_D_SYS = TRANSDD_SYS+TRANSBD_SYS
REFL_SYS=(BB(m+1)+D(m+1))! /(GBM+GDF)
ELSEIF (icfcltp(icomp, icfctp, 3) .eq. iRollerBlind) then
TRANSBB_SYS = 0.0! /GBM ! if layer is module, no direct radiation is transmitted
TRANSBD_SYS = BD(1)! /GBM
TRANSDD_SYS = DD(1)! /GDF
TRANS_D_SYS = TRANSDD_SYS+TRANSBD_SYS
REFL_SYS=(BB(m+1)+D(m+1))! /(GBM+GDF)
ELSE
TRANSBB_SYS = BB(1)! /GBM
TRANSBD_SYS = BD(1)! /GBM
TRANSDD_SYS = DD(1)! /GDF
TRANS_D_SYS = TRANSDD_SYS+TRANSBD_SYS
REFL_SYS=(BB(m+1)+D(m+1))! /(GBM+GDF)
ENDIF

!Layer Absorptance Calculation
DO i=1, n-2, 1
xx=2*i-1
Bminus(n-i)=BB(xx)
Dminus(n-i)=D(xx)
xx=2*i
Bplus(n-i)=BB(xx)
Dplus(n-i)=D(xx)

ENDDO
Bminus(1)=GBM
Bplus(1)=BB(m+1)
Dminus(1)=GDF
Dplus(1)=D(m+1)
DO i=1,n-2,1
IF (icfcltp(icomp,icfctp,i) .eq. iVenBlind) THEN
   SS(i)=Ra*(Dminus(i)-Dplus(i)+Dplus(i+1)-Dminus(i+1)) !/ (GBM+GDF)
   AbsSol(i)=SS(i)
ELSEIF (icfcltp(icomp,icfctp,i) .eq. iRollerBlind) THEN
   SS(i)=Rc*(1-PVe)*Bminus(i)
   AbsSol(i)=SS(i)
   PVout=0.001*Rc*PVe*Bminus(i)
   PVoutsum=PVoutsum+PVout
ELSE
   SS(i)=(Bminus(i)-Bplus(i)+Bplus(i+1)-Bminus(i+1)+Dminus(i)
   &                     -Dplus(i)+Dplus(i+1)-Dminus(i+1)) !/ (GBM+GDF)
   AbsSol(i)=SS(i)
ENDIF
ENDDO

IF (GBM.lt.0.01) THEN
   GBM=0.0     ! reset back to zero
ENDIF
PRINT *, 'Pvsum', PVoutsum
RETURN
END
Appendix C: Surface temperature of solar cell in ITPVB

As each ITPVB slat consists of concentrated photovoltaic modules and solar cells, all the direct radiation would hit and be absorbed on small surface of the solar cell. Thus, the high intensity solar radiation would make a high surface temperature of solar cell. On the other hand, because the module part of ITPVB only absorbs diffuse radiation, the surface temperature of module would be much lower than solar cell. However, in the design of the product of ITPVB: SolarSwing Energy, one ITPVB slat consists of 16(4x4) modules and cells. The cell size is 1.4mmx1.4mm. If assuming one direct radiation ray is 500W/m², the concentration ratio is 800 and 100% of this ray is absorbed, only 0.784W radiation is absorbed. This much absorbed radiation would not lead to an extremely high temperature. Figure 1 shows the solar cell surface temperature at different concentration ratio. The surface temperature increases with the concentration ratio. Thus it can be assumed that if the concentration is 800, the surface temperature would be extremely high. This situation is not realistic. Thus the simulated surface temperature of solar cell cannot be trusted. Furthermore, in the reality, the heat on the solar cell surface loses by the conduction with the connection of module (Figure 2a). There exists thermal bridge. In the simulation case, because ESP-r consider every node on one surface has the same temperature, there is no temperature transitions (Fig.2b). This difference also makes the cell surface temperature high in the simulation result. Thus, it makes the simulated surface temperature less trustful.

Figure 1 simulation results of ITPVB’s solar cell surface temperature at different concentration ratio

![Figure 1](image1.png)

Figure 2 ITPVB’s surface temperature’s (a) assumption with concentration ratio in reality; (b) simulation results’ sketch

![Figure 2](image2.png)
Appendix D: Solar radiation flow through DSF, slat-blind in-between DSF, PV-panel in-between DSF and ITPVB in-between DSF in different sky types and seasons

- Sunny Winter Day

**Case 1**
- R: 264W/day
- A_{hi}: 651W/day
- 2163W/day
- 1115W/day
- A_{el}: 345W/day
- R: 170W/day
- T: 600W/day

**Case 2**
- R: 519W/day
- A_{hi}: 1512W/day
- 2163W/day
- 1115W/day
- A_{el}: 204W/day
- R: 237W/day
- T: 204W/day

**Case 3**
- R: 155W/day
- A_{hi}: 659W/day
- A_{el}: 1349W/day
- 2163W/day
- 1115W/day
- A_{el}: 326W/day
- A_{hi}: 641W/day
- R: 148W/day

**Case 4**
- R: 155W/day
- A_{hi}: 659W/day
- A_{el}: 1349W/day
- 2163W/day
- 1115W/day
- A_{el}: 486W/day
- A_{hi}: 641W/day
- R: 221W/day
- T: 408W/day
Cloudy winter day

Case 1
- R: 11W/day
- 92W/day
- 955W/day
- A_h: 28W/day
- A_h': 303W/day
- T: 53W/day
- T: 179W/day

Case 2
- R: 23W/day
- 92W/day
- 955W/day
- A_h: 64W/day
- A_h': 574W/day
- T: 5W/day
- T: 179W/day

Case 3
- R: 6W/day
- 92W/day
- 955W/day
- A_h: 28W/day
- A_h': 58W/day
- A_el: 28W/day
- A_el': 278W/day
- A_h: 550W/day

Case 4
- R: 6W/day
- 92W/day
- 955W/day
- A_h: 28W/day
- A_h': 58W/day
- A_h: 417W/day
- T: 349W/day
R – Reflection
A_h – absorption for heat gain
A_el – absorption for electricity generation
T – Transmission
Red flux – Direct radiation
Orange flux – Diffuse radiation
Case 1: DSF without shading devices
Case 2: Slat-blind in-between DSF
Case 3: High efficient PV panel in-between DSF
Case 4: ITPVB in-between DSF
## Appendix E: Spreadsheet of Primary Energy Indicator

<table>
<thead>
<tr>
<th>CASE</th>
<th>Climate</th>
<th>Walls orientation (thermal mass)</th>
<th>Walls insulation</th>
<th>Space (kWh)</th>
<th>Space Coverage</th>
<th>Heating (kWh)</th>
<th>Cooling (kWh)</th>
<th>Electricity electricity demand (kWh)</th>
<th>Solar electricity demand (kWh)</th>
<th>Heating System</th>
<th>Cooling System</th>
<th>Electricity demand (kWh)</th>
<th>Electricity demand (kWh)</th>
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