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Coupling Energy and Daylighting Simulation
for Complex Fenestration Systems

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This chapter introduces the themes that have driven the development of the project through the analysis of energetic and economic context where we live and where shopping malls upholster an important role being the mirror of current society. In this context was born the commONEnergy project, with the aim to make green those "energivore" system that are shopping malls. Here the necessity to have a tool that allows to evaluate with a good accuracy the energy performance of the building and that take in account important aspects as daylighting.

1.1 EU Context

In the European countries the building sector is the top energy-demanded sector before industry and transport with the 40% of the energy consumption. Over a third of EU carbon emissions are related to buildings. Building sector can be divided in two macro categories as shown in figure 1.1. Residential building is the relevant part of the building stock, 75%, and as a quite homogeneous distribution in terms of constructive configuration and usage, that make more easily the treatise and the definition of a energy guideline to follow.

Non-residential buildings enclose an heterogeneous and complex building typology compared with the residential stock due to the usage pattern, energy demand and technologies construction. For this reason, in the EPBD the non-residential part is divided into seven sub-categories: Wholesale and Retail, Offices, Educational, Hotels and Restaurants, Hospitals, Sports facilities and Others. Figure 1.2 shows the energy consumption in terms of finale energy consumption (total energy consumed by the user) per square meter in non-residential buildings in EU countries.

Figure 1.1 shows also that the largest non-residential floor area has occupied from the category Wholesale and retail with the 28%. This result is due to the heteroge-
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1.2 Shopping malls energy consumption

Due to refrigeration, power lighting, air-conditioning, heating and ventilation, shopping centres are the most energy-demanding buildings, consuming four to five times more energy per square meter than residential buildings. In accord with a research of Schönberger H. [27] the total energy consumption for food and non-food stores in European are reported in table [1.1]. As we can see the relevant demand comes from the food store type due to the high power consumption for food refrigeration and merchandise presentation in the fresh produce area.

That difference is better visible in the pie charts, figure [1.3]. We can observe that in the first chart, relative to the hypermarket with food store, the largest cut regards the consumption for food refrigeration with almost the 45%, following by store lighting and heating and air-cooling. In the second chart the first consumption is owing to the shop lighting with the 50%, following again by heating and air-conditioning. Two main results are visible: the first confirm that the refrigeration has the maximum incidence where present but also the lighting plays a decisive role in the energy consumption.
consumption being the second and the first source of energy demand in both the pie graph with relevant percentage.

However, the composition of the energy demand varies from one retailed to another. For example, the electricity consumption of appliances in electronics stores is higher than in other kinds of shops, which are more dependent on lighting, such as furniture.

Also the mean consumption change with the typologies of shop; as shown in a study conduct on the specific energy consumption in a typical shopping malls in Centre Europe composed by 238 shops [28]. Table 1.2 show the different use of energies per different shop categories.

An important aspect that influence directly the energy demand of a shopping mall is his constructive configuration, such as geometry, size, construction materials, envelope, technologies for heating, cooling and hot water supply, lighting fixture. In table 1.3 are show the energy consumption for the size variation of centre. As expected the average consumption decrease with the increasing of the shopping mall size from 280 to 228 kWh/m²a. For the common areas is not available a specific analysis therefore has taken a constant value.

Taking in to account all these aspect has been possible define the total energy
1. Introduction

1.2. SHOPPING MALLS ENERGY CONSUMPTION

<table>
<thead>
<tr>
<th></th>
<th>Energy Consumption [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Store</td>
<td>500 - 1000</td>
</tr>
<tr>
<td>Non-Food Store</td>
<td></td>
</tr>
<tr>
<td>Area &lt; 200 m²</td>
<td>270</td>
</tr>
<tr>
<td>Area &gt; 300 m²</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 1.1: Energy consumption in different typology of stores

![Energy Consumption Chart](image)

Figure 1.3: Share of total energy demand in retail building [29]

...consumption for shopping malls per 30 countries (EU28 plus Norway and Switzerland) [4].

Is necessary keep in mind that these results are the first calculated until now for this building category therefore does not exist reference values to make comparison.

Figure 1.4 shows the total final energy consumption without the energy used for mobility. As we can see the first five countries, with the largest consumption in descending order, are UK, Germany, Spain, France and Italy. These five countries account for the 19% of the total energy consumption of the 30 countries.
1.2. SHOPPING MALLS ENERGY CONSUMPTION

<table>
<thead>
<tr>
<th>Anchor Stores</th>
<th>Clothing</th>
<th>Hobby</th>
<th>Home</th>
<th>Supermarket</th>
<th>Other Services</th>
<th>Not categorized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of shops</td>
<td>14</td>
<td>89</td>
<td>6</td>
<td>15</td>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>Mean floor area [m²]</td>
<td>3205</td>
<td>421</td>
<td>241</td>
<td>645</td>
<td>824</td>
<td>174</td>
</tr>
<tr>
<td>Mean consumption [kWh/m²a]</td>
<td>158</td>
<td>180</td>
<td>206</td>
<td>244</td>
<td>456</td>
<td>385</td>
</tr>
</tbody>
</table>

Table 1.2: Mean floor area and specific energy use in different shop categories

<table>
<thead>
<tr>
<th>Specific energy consumption of shop [kWh/m²a]</th>
<th>Specific energy consumption of the common area [kWh/m²a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small shopping centre</td>
<td>280</td>
</tr>
<tr>
<td>Medium shopping centre</td>
<td>263</td>
</tr>
<tr>
<td>Large shopping centre</td>
<td>248</td>
</tr>
<tr>
<td>Very large shopping centre</td>
<td>228</td>
</tr>
<tr>
<td>Total average</td>
<td>261</td>
</tr>
</tbody>
</table>

Table 1.3: Energy consumption per shop dimension

Figure 1.4: Total final energy consumption in EU shopping centre buildings

1.2.1 Shopping malls inefficiencies

The main typical inefficiencies that we can find in shopping malls centre regarding [26]:

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1. Introduction

1.2. SHOPPING MALLS ENERGY CONSUMPTION

- energy (e.g. building physics and technical solutions);
- comfort (e.g. thermal and visual);
- logistic and operation (e.g. maintenance).

Particular attention will be take to the inefficiencies due to the comfort and the the difficulties in providing an effective retail environment. In fact should consider the comfort aspect at the same importance level of the energy problem. Since these aspect are directly connect, an high comfort level influence the amount of energy used, and obviously comfort affect health and human well-being.

**HVAC** One of the more important lack regards an inadequate HVAC systems. These systems have an important role on internal comfort; both in terms of indoor air quality and thermal (heating and cooling) condition. The main inefficiencies owing to the old systems used which often are not design in appropriate way, and are not able to satisfy the cooling/heating demand. This is the principal cause of energy waste. Then, there are energy loss in the ventilation systems and in the distribution systems for heating and cooling. The system efficiency decrease for the improper maintenance, this issue weigh also on the cost, operating and repairing, and on the operative life of the system. Heat pumps and bioclimatic solution are total absent, also cogeneration and trigeneration.

**Building Envelope** Other systemic inefficiencies regards the building envelope, in particular the low levels of thermal insulation in wall, floor, windows and ceiling. A correct envelope insulation reduce the heat loss and allow to dimension the heating and cooling systems with a better precision in order to reduce energy waste. Principal lacks due to windows and doors low quality, shortage of technological glazing solution, lack of dynamic and static shading device for thermal and lighting control. Air lacks and cracks in the walls represent a problem for infiltration and humidity with mildew formation. Wrong use of pain and material on the exterior reduce the energy saving for cooling, reflective colour help the insulation in summer season. Green roofs are quite a little used. Other inefficiencies regards the filed of food refrigeration, motors and drivers, cleaning and maintenance, water usage, control systems, logistic and retrofitting process [26].

**Lighting** The theme of lighting is particular delicate; the results of several questionnaires conduct within CommONEnergy project on shopping malls character (owners and manager, tenants, customers) shows that lighting and daylighting are the most important actions to undertake in order to improve the shopping mall environment. In particular toward the improvement of energy efficiencies of artificial lighting but also the reduction of this, where possible, in favour of the use of daylighting. Several studies have demonstrated the weight of lighting on energy balance in retail sector; figure [1.5] show the results of a study by Di Laura David L. [10], here lighting
accounts for 42% of total electricity use in retail building. Other studies conduct in Germany estimate that about 60% of energy demand accounts for lighting. The percentage of incidence on energy demand of lighting depend also from the shop use as shown in figure 1.6 Supermarkets have the highest consumption cause of the numerous presence of light and for the different light typology (i.e. corridors, fresh food zone).

![Figure 1.5: Electricity use of retail facilities](image)

![Figure 1.6: Energy cost of lighting for different types of shop](image)

Inefficiencies are tied at the exasperated use of artificial lighting without consider
the use of daylighting which is not only a free source that allows to take advantage of lighting and heating but affects also the human well-being and the health. Shops are often project without consider the daylighting share. This because owners are afraid of negative impact like glare and high solar gain, that made of sunlight an enemy to avoid.

However, in some case the inefficiencies are exactly the excessive entrance of daylight that cause thermal and visual discomfort. Often the centres have large façade, devoid of shading system, that allow the entering of sunlight without control on the correct amount of daylight.

A key point in energy efficient lighting design is the choice of efficient lamps, which produce the proper spectrum and offer the required operating features [25]. This problem regards the direct cost in terms energy consumption and the occasional cost due to the replacement of light source after the end of life, reduce the maintenance cost using efficient light is possible, for example incandescent lamps have a life of 1000 h versus the 50000 h of LED life.

Often the gloss floor surfaces misguide the person’s attention inducing virtual mapping. This behaviour can not be accepted; exist other solution, more efficient, that support the light flow through the space as bright paint with high reflection factor.

1.3 CommONEnergy

CommONEnergy born to reduce the energy demand of retail sector with the purpose to meet the EU target on energy saving within 2020. The objective of the project is re-conceptualize shopping malls through deep retrofitting in order to reduce energy consumption with a sustainable cost. The project will encourage the development of sustainable shopping centres by supporting the energy efficient rehabilitation of existing shopping centres and providing knowledge which will encourage the efficient design of new shopping centres.

The performance targets can be summarized as follow [7]:

- Up to 75% reduction of energy demand;
- Power peak shaving;
- 50% increased share of renewable energy source favoured by intelligent energy management and effective storage;
- Improvement of comfort and health conditions for occupants and visitors;
- Realised while respecting high indoor environmental standards and short pay-back times(below 7 years).

The strategies to aim these targets are the use of a holistic approach considering all technical, economic, environmental and social aspects shifting from a single-action refurbishment to a Systemic Retrofitting Approach, figure [1.7] that involves
innovative technology solutions and methods backed by support tools.

![Figure 1.7: Systemic Retrofitting Approach work flow](image)

The project gathers twenty-three partners all around the EU, figure 1.8. Each partner is engaged in a specific aspect of the design. Through the integrated approach, that involves owners, designer, manufacturer all coordinated by Eurac Research, all partners share their work in order to reach the performance targets. The solutions will be applied to three real cases study: Italy, Norway and Spain (figure 1.8), which represent for building typologies, architectural features and climatic condition the variety of shopping mall stock in Europe, therefore is possible extend the results obtained to a huge number of buildings.

![Figure 1.8: Partners and demo case distribution](image)
1.3.1 Task 4.1: Coupling thermal and lighting simulations

To achieve the target the development has divided in seven work packages. My work belong to WP4 that regards solutions for enhancing energy efficiency [8].

As seen in section 1.2.1, is necessary achieve energy saving and indoor comfort within these energy consumer systems, it can be done through a rational use of the natural resource, and in particular of daylighting. One of the best ways to provide this improvement is the use of Complex Fenestration Systems (CFS), these systems allow a good management of the solar gain both in terms of energy saving for heating, cooling and artificial lighting and in terms of visual comfort with the preferential use of the daylighting within the interior spaces.

Here the importance of possess a tool that have an holistic approach; that can manage at the same time both thermal and daylighting simulation in order to have prompt results and reduce the time necessary to oversee the software separately.

Thus, between the objectives of the working package there is the development of this new tool that allows dynamic daylighting simulation, with Radiance, for CFS within a building energy modelling software, in our case TRNSYS, since it is the software chosen in CommONEnergy project to carried out thermal simulation.

The goals of the work can be summarized in the following three points:

1. Couple thermal and daylighting simulation for CFS;
2. Flexibility about the control strategies;
3. Optimization of CFS system with respect to:
   - visual comfort (adequate illumination, glare);
   - thermal comfort (solar gain);
   - energy (heating cooling, lighting).
In this chapter will be an overview about the current software able to couple thermal and daylighting simulations for simple and complex fenestration system. We will see the current features of TRNSYS and Radiance in respect to complex fenestration system. Finally before to introduce the main chapter will be shown the principal daylighting index used to evaluate the amount of daylighting within the space.

2.1 Radiance and building simulation

Currently already exist several software that gather both simulations in the same tool. Some of these are the feature to carrying out daylighting simulation for CFS using the three phase method of Radiance.

OpenStudio Developed by National Renewable Energy Laboratory (NREL), this software carry out thermal and lighting simulation using energy plus as engine for energy simulation and Radiance for daylighting simulation. The daylighting simulation that can be performed are \[\text{[24]}\):

- "point-in-time" simulations using classic Radiance programs (rpict and rtrace);
- daylight coefficients analysis for illuminance maps;
- annual climate-based daylight simulation, optionally using the three-phase method with bidirectional scattering distribution functions (BSDFs) to represent windows in a variety of configurations.

To what extent the last point, in order to use the three phase method is necessary the knowledge of the BSDFs matrix that characterize the fenestration system; NREL
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2.1. RADIANCE AND BUILDING SIMULATION

make available a library about building component [17] for OpenStudio that provide also these data. Energy plus also allow to define CFS through their BSDFs in order to evaluate solar heat gain on short wave in according to ISO 15099 [1]. So, an importance feature is the common input about CFS characteristics for both simulations. OpenStudio use the same model both for Energy Plus and Radiance, after importing the geometry is possible assign to it the materials (surfaces reflectance, glazing transmission). Once set the geometry with materials definition has to be choose the daylighting analysis objects between: illuminance maps (analysis grid), daylighting control points (photosensors), glare sensors [17]. In the simulation radiance take the uncontrolled windows together, instead the controlled windows are logically grouped by: space, orientation, distribution or schedule. As results the simulation produces annual illuminance schedule for each window group and shade combination, but without the possibility of visualization and windows group combination. Running the simulation Energy Plus takes in account the lighting schedule produced with Radiance and evaluates the electric lighting control on daylighting distribution.

**DesignBuilder**  As OpenStudio, also this software uses EnergyPlus and Radiance as engine calculation. DesignBuilder provides several types of daylighting calculations [9]:

- map analysis, daylight distribution on working plan through contour map;
- grid analysis, daylight statistic that includes average, min and max daylighting factor and uniformity factor data;
- generates reports to obtain daylighting credits in the main protocols (LEED, BREEAM and Green Star);
- photo-realistic rendered images generated using Radiance.

Daylight illuminance results are use in EnergyPlus for the electric lights control evaluating then energy saving in the thermal simulation. Three phase method has not implemented then the software is not able to provide daylight simulation for complex fenestration system.

**Diva for Rhino**  Is a plug-in for Rhinoceros, CAD modelling software, that allows daylighting and simple energy simulation. For the part that regards daylighting simulations Diva uses Radiance and Daysim, giving a huge range of simulations [11]:

- radiation maps;
- photo-realistic rendering;
- climate-based daylighting analysis;
- annual and individual time step glare analysis;
2.1. RADIANCE AND BUILDING SIMULATION

- sDA / ASE calculations;
- LEED v4 metrics based simulations.

Diva gives also the possibility to simulate CFS through the use of BSDFs data, it is possible defining the BSDFs as custom Radiance materials. Even though this solution gives results more reliable then the simulation with classic materials is not still accurate as the Three or Five Phase Method that is not implemented in Diva. To what extend the energy simulation, Diva uses EnergyPlus as engine simulation, but his capabilities are limited to a single thermal zone. The simulations are automatically connected within the software; EnergyPlus uses lighting and shading schedules generated by Diva/Daysim simulations.

The geometry used in the simulations, thermal and daylighting, is not the same. For the thermal model several simplifications must be made cause while daylighting needs a volumetric geometry with more details possible, thermal model has to build as plans.

Using Diva in Grasshopper environment [16], an algorithmic modelling for Rhino, is possible also run parametric simulations and obtain real time results, both thermal and daylight.

**HoneyBee & LadyBug** Ladybug & Honeybee is an environmental add-on for Grasshopper that allows parametric daylighting and thermal simulation. Honeybee & LadyBug connect Grasshopper with Radiance, Daysim, EnergyPlus and OpenStudio, using as daylighting simulation engine Radiance and Daysim. Thus, the features and capabilities for daylighting simulation are the same of Diva4Rhino, without the limit on the thermal zoning for energy simulation.

**ESP-r** Is a simulation environment for energy performance in buildings. Allows to export Radiance geometry to perform daylighting simulations. This software is capable to treat the BSDFs matrix that characterize complex fenestration systems implementing the "Black Box Model"[15]. Not easy to use, usually used in researcher activity.

**BCVTB** Building Controls Virtual Test Bed [3] is not a proper energy or lighting simulation tool but is a software environment that gives the capability to couple different software programs and share data between them, figure 2.1. As shown in the figure 2.1 Radiance and EnergyPlus have already coupled, also Radiance’s Three Phase Method was implemented to perform daylighting simulations for CFS by McNeil [22]. The power of this software is within the possibility to use custom control algorithms in dynamic daylighting simulations and the ability to connect manufacturer’s control hardware to test systems without the need to reveal proprietary algorithms.

After this analysis on the main simulation tools that contain Radiance for daylighting simulations we can observe the existence of some barriers that burden the
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2.2 TRNSYS - THERMAL SIMULATIONS

Figure 2.1: Possible connection for building simulations

theme. All software use Radiance functionalities to perform daylighting simulations (table 2.1) for simple glazing systems, which with the new daylighting strategies are not more useful. In fact these new technologies, that redirect sunlight into spaces in efficient mode and avoid glare but also improve the energy performance of the building controlling solar gain, have a peculiar radiant behaviour compared with the classic solutions that can be described through the bidirectional scattering diffusive function (BSDF) matrix. Thus, result inappropriate use simplified models to provide simulations with CFS instead became essentially the use of these data, BSDFs, in order to reach reliable and realistic results in thermal and daylighting simulations. Currently OpenStudio, Diva, HB & LB and BCVTB can manage BSDFs data, but Diva and HB & LB only as Radiance material in the classic simulation instead OpenStudio and BCVTB have in addition implemented the Three Phase Method for daylighting simulations. If we want to do a deeper comparison the only software that can run BSDFs for thermal and daylighting simulations, has the ability to provide the Three Phase Method for daylighting simulations and above all is user-friendly for the designer is OpenStudio.

2.2 TRNSYS - Thermal simulations

Within CommONEnergy project the software chosen to carry out building energy simulations is TRNSYS (TRaNsient SYstem Simulation). Currently the last version
is the 17.01. TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings [31]. One of the key factors in TRNSYS is his modular structure in which was separated the complex components that made the building, as solar, photovoltaic, heating/cooling systems. These components called "Type" may be organize on the TRNSYS's deck and connect each other by way of "pipes" that link input and output of the several types in order to share informations during the simulations. The model is typically build by connecting components graphically in TRNSYS Simulation Studio. A mathematical model describes each component and during the simulation TRNSYS solves the set of algebraic and differential equations within the time-step chosen until the equations are verified. The main Type that provides thermal simulations is the number 56 relative to the multi-zone building model. Due to the complexity of the characteristics in multi-zone building the detailed information about every zone of the building are describe in an other environment called TRNBuild. In TRNBuild we can set all those parameters that influence the thermal behaviour of the building such as building structure details (material property), internal gains, heating/cooling/lighting
schedules, infiltration, etc. Geometry can be drawn in Google SketchUp\textsuperscript{TM} thanks to a plug-in, TRN3D, that allows to create the thermal zoning and generate the .idf file of input for TRNSYS. Also, thanks to the DLL-based architecture users and third-party developers may easily add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN, etc.).

2.2.1 Fenestration systems and shading devices in TRNBuild

To what extent the windows typology, within TRNBuild is not allowed define window properties used in the simulation, in fact from the relative window (figure 2.2) is possible choose within a library a window with define characteristics that cannot be changed. Is also possible import custom windows generated with window 6.3, see section ?????. Nevertheless, there is no way to use a BSDF data to simulate the thermal flux throughout a complex fenestration system.

Thus, at the state of art is only possible simulate simple fenestration systems and provide false shading, internal and/or external, through a shading factor that gives the ratio of windows covered by the shading device. The shaded part of the windows is considerate as an opaque surface without evaluate a specific behaviour of the light that pass through the shading, due to the complex geometry of shading device (i.e. louver with particular shape).

In conclusion, TRNSYS limits are:

- thermal simulation for simple windows and shading devices;
- no thermal simulation of complex fenestration systems through BSDFs data;
- no daylighting simulations of any type.

2.2.2 On going development

**Type 56 BSDF** In order to make TRNSYS in step with the current technologies, Trnssolar’s researcher are developing a new version of the Type 56 that include the usage of BSDF data for short-wave radiation model in which the thermal model is based on ISO 15099 [1].

For modelling the system are required same properties of the shading layer:
- BSDF data for transmission, reflection front and back;
- angular absorption, calculate from solar transmittance and reflectance of BSDF data;
- IR transmission, IR reflection front, IR reflection back;
- front opening ratio.

Then is necessary define the complete system, glazing & blinds, in window 6.3/7 and generate the BSDF for the entire fenestration system that is given in input to the Type 56; the process is shown in figure 2.3.

![Complex fenestration model](image)

**Figure 2.3:** Complex fenestration model

The type is not yet in commerce being still a prototype in validation phase. Some results were presented at the TRNSYS Userday of the last May on the comparison between the new Type 56 BSDF and EnergyPlus. Both software use the same model algorithms:

- Identical external solar modeling (Perez, 1999);
- Almost internal longwave radiation modeling (view factor);
- Identical CFS model based on BSDF data and ISO 15099;
Different modeling of:
- Fictive sky temperature (external LW radiation);
- External/Internal convection transfer coefficients.

And have similar database for simulation of CFS. The preliminary results gathered show that there is an excellent accordance for regular glazing systems without shading and small deviation for glazing with blinds [20].

**Green Lizard** It is a plug-in that implements TRNSYSlite 3D with daylighting simulation in Grasshopper. The plug in converts Rhino geometry more additional information to generate the *.b17 format and the corresponding *.d17 file to run the simulation. The *.b17 is also used as geometry for daylighting simulations. However, Lizard provides the current TRNSYS features without the possibility to manage BSDF file, so also the daylighting simulations, that without the Three Phase Method, allow the evaluation of daylighting factor and illuminance on a grid. Then the artificial lighting control can be passed from daylighting to thermal model.

An other obstacle regards the inability to provide multi zone building simulations, in fact the calculations are limited to a single zone. Nevertheless, is possible couple multiple "green lizard", one for each zone, in order to simulate multi zone building.

![Green Lizard simulation](image)

**Figure 2.4: Green Lizard simulation**

### 2.3 Radiance - Three Phase Method

Radiance is a software developed in the Environmental Energy Technologies Division of Lawrence Berkeley National Laboratory in Berkeley, California, by Greg Ward and the Lighting Systems Research group. It is a accurate tool for predict the visible radiation in a space using the back ray-tracing methodology. This method
consist in follow the light path (specular reflected, transmitted and refracted) from the reception point (eyes or sensors) into the scene to the light source, as shown in figure 2.5.

![Figure 2.5: Backward ray-tracing](image)

In the practise is consider the best and more flexible software for lighting simulation, in fact is used as calculation engine in the most lighting design software available. Is also the most validate lighting simulation tool. Probably the only drawback of Radiance is that it is not a user-friendly tool. It does not have a graphical interface, and requires considerable amount of practice in order to enable the user to use it properly [23].

### 2.3.1 Three Phase Method

Is a method develop in Radiance that perform annul daylighting simulation for complex and/or dynamic fenestration system. The name is due to at the sub division of light path in three step (figure 2.6) defined in the calculation by three matrix. The three phases of the transfer flux are:

1. from sky to exterior of window, described by Daylighting matrix (D);

2. between the the interior and exterior of the window, described by the BSDF matrix called also Transmission matrix (T);

3. from the interior of the window to the sensor points, described by the View matrix (V).
The results is achieved by multiplying the sky vector/matrix for matrix listed above.

\[ i = VTDS \]  \hspace{1cm} (2.1)
\[ I = VTDS \]  \hspace{1cm} (2.2)

where, by McNeil [21]:

- \( i \) = point in time illuminance or luminance result;
- \( I \) = matrix containing time series of illuminance or luminance result, annual simulation;
- \( V \) = view matrix, relating outgoing directions on window to desired results at interior;
- \( T \) = transmission matrix, relating incident window directions to exiting directions (BSDF);
- \( D \) = daylight matrix, relating sky patches to incident directions on window;
- \( s \) = sky vector, assigning luminance values to patches representing sky directions;
- \( S \) = sky matrix, a collection of sky vectors.

The V and D matrices are created with a Radiance simulation. The T matrix can be created using LBNL window software, by simulation (i.e. TracePro or Radiance).
2.4. POSSIBLE COUPLING

Analysing the current features of TRNSYS and Radiance what can be done to aim the objectives defined in section 1.3.1 is implement in TRNSYS a Type that allows daylighting simulation using the Radiance’s Three Phase Method. It can be done cause the TRNSYS’s architecture based on DLL allows to create custom Type using the common program language, as C, C++, Fortran. In this way, is possible locate both Type on the same TRNSYS deck and connect each other with the same input, or rather the same BSDF data, as shown in figure 2.7 where the informations exchanged between the Radiance’s Type and the Type 56 BSDF may be illuminance values, BSDF data used in the simulation, the response of a thermal control or what we need to share.

This structure can also allows to define an own custom control for daylighting or thermal or both. Then, we obtain a control that allows us to have an absolute flexibility about we want to obtain in the interior space in terms of daylighting and thermal gains; in fact this control may allows us to define, for example, a daylighting based control in the summer season in order to avoid glare and prevent the right amount of light in the inner spaces and a thermal based control in the winter season if we want to reduce the energy consumption for heating.

![Figure 2.7: Work flow of the coupling](image)

Before to go on is necessary define what is the BSDF and why is so much important chose this data as input for the simulations.

2.4.1 Bidirectional Scattering Distribution Function

Is a mathematical function \( f(\theta_i, \phi_i; \theta_o, \phi_o) \) which describes the way in which a light flux, or more in general, an electromagnetic wave behave when meet an object. This function needs of two couple of angle in input for the incoming and outgoing ray, see figure 2.8 then gives as result the value defining the ratio between the incoming and the outgoing light energy [32].
Usually the BSDF is split in two separate parts, the BRDF (Bidirectional Reflectance Distribution Function), that is the first function defined around 1965 by Fred Nicodemus and describe the reflected scatter distribution of a light ray incident on a surface’s point, and the BTDF (Bidirectional Transmittance Distribution Function) that describe the transmitted scatter distribution of the same light ray as shown in figure 2.9.

In the definition of bidirectional property of the Complex Fenestration Systems these BSDF data assume the form of matrices, these matrices describe the incoming and outgoing rays from a defined angles obtained dividing a semi-hemisphere in 145 patches according to the Klems method \[18, 19\], obtaining a square matrix 145x145. The equation 2.3 by JH \[18\] describe the matrices construction using the Klem method:

\[ I_j(\theta_o, \phi_o) = f_{j,k}(\theta_i, \phi_i; \theta_o, \phi_o) E_k(\theta_i, \phi_i) \]  (2.3)

where:

- \((\theta_o, \phi_o), (\theta_i, \phi_i)\) describe respectively the outgoing and incoming direction of the radiation;
- \(I_j(\theta_o, \phi_o)\) represent the outgoing radiance on the \(j\)th patch;
- \(E_k(\theta_i, \phi_i)\) represent the incoming irradiance on the \(k\)th path;
- \(f_{j,k}(\theta_i, \phi_i; \theta_o, \phi_o)\) is the BSDF for the couple of angle defined by the couple of patches considered.
What the $f_{j,k}(\theta_i, \phi_i; \theta_o, \phi_o)$ function describe is defined choosing the radiance $I$ and irradiance $E$ input, in particular combining the radiance that pass through the layer, from front to back side, or the radiance which is reflected from the front side with the irradiance incident on the front surface of the layer or on his back side, inner layer, we obtain four combinations for the BSDF matrices:

- front transmission
- back transmission
- front reflection
- back reflection

that can be evaluated for visible wave length and solar wave length.

For example the Three Phase Method to compute daylighting simulation uses the BSDF back transmission matrix in the wave length of visible. Instead for the thermal simulation in TRNSYS are required all the four matrices, see section 2.2.2. This method used to describe the behaviour of the CFS gives great flexibility and accuracy in evaluating the optical and thermal feature of these systems.

Seen how these new technologies for improving thermal and visual comfort are getting a foothold is necessary first take in account accurate data that describe in deep the CFS behaviour, that is the BSDF, then use simulation tools which are able to treat these data in order to obtain reliable results about thermal and optical response of the
fenestration system. Thus, for our scopes we cannot exclude the use of BSDF within both the simulation tools.

2.5 Daylighting index for buildings

This paragraph is necessary to understand which daylighting parameters play an important role in the definition of adequate light quality within the building space.

**Daylighting factor (DF)**  Daylight Factor is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies. Usually the illuminance values for an overcast sky is around 10000 lux the corresponding daylighting factor will be 2 percent, due to 500 lux required in indoor space /10000 lux present outdoor [6].

**Daylight Autonomy (DA)**  The first definition was given in 1989 in a Swiss norm that define the Daylight autonomy as” the percentage of the year when a minimum illuminance threshold is met by daylit only”. In 2001 Reinhart and Walkenhorst redefined daylight autonomy as the percentage of the occupied times of the year when the minimum illuminance threshold at the sensor point is met by daylight alone [6].

**Useful Daylight Illuminances (UDI)**  Proposed by Mardaljevic and Nabil in 2005 [6]. The aim is to determine a useful light levels for the users, not too dark nor to bright. UDI results are divided in three sub-metrics that are the percentages of the occupant time of the year when the UDI was achieved (100-2000 lux), fell-short (<100 lux) or was exceeded (>2000 lux). Over the last limit we are in a discomfort situation due to glare.

**Continuous Daylight Autonomy (DAcon)**  Proposed by Rogers in 2006. Similar to the Daylight Autonomies but instead of the percentage on a sensor point is given a credit when daylight illuminance lies below the minimum illuminance level. The credit is defined as the illuminance level/illuminance threshold.

**Spatial Daylight Autonomy (sDA)**  It is described in IES LM-83. Is defines as the percentage of floor area that is above a minimum daylight level, 300 lux, for 50% of the time or more during the occupancy hours [2].

**Annual Sunlight Exposure (ASE)**  Is the number of hours per year at a given point where direct sun is incident on the surface. This index is defined in IES LM-83 with threshold values, in particular is defined as the percentage of work hours during which the light level from direct sun alone exceeds the threshold, 1000 lux, for 250 hours [2].
Bibliography


[31] TRNSYS. URL: http://www.trnsys.com/