THERMAL AND OPTICAL MODELING OF COMPLEX FENESTRATION SYSTEMS WITHIN THE CONTEXT OF BUILDING INFORMATION MODELING

M.Boudhaim[1], T.Pflug[2], B.Bueno[2], M.Siroux[1], T.Kuhn[2]

[1] INSA Strasbourg, Laboratoire ICUBE, Université de Strasbourg,
Strasbourg 67000, France,
[2]Solar Façade group, Fraunhofer Institute For Solar Energy Systems,
Freiburg 79110, Germany

ABSTRACT

Building Information Modeling (BIM) is a process involving the generation and management of numerical representations of physical and functional characteristics of building components. This process involves file formats that can be exchanged or networked to support decision-making, avoiding redundancy and miscommunication, which often lead to non-optimized and non-efficient solutions. Although significant effort has already been devoted to the BIM representation of the building skeleton construction, the energetic and comfort aspects of the building skin are not yet fully represented in BIM. This paper will focus on the thermal modeling of complex fenestration systems (CFS).

The way of calculating the thermal properties and heat transfer of CFS in detailed building simulation programs is to represent it with a layer-by-layer nodal model such as in ISO15099. While this type of thermal models is accurate for conventional glazing systems such as for example double and triples glazing, it requires strong assumptions in the case of three-dimensional structures (e.g. venetian blinds) and porous layers.

Semi-empirical models, in which the complexity of a system is captured by one or various experiments, constitute an alternative to layer-by-layer heat transfer models. Kuhn et al. presented a “Black-Box” model to predict solar gains through CFS in building simulation programs. The model requires angularly resolved solar heat gain coefficients, solar transmittance and U-value, which can be analytically derived or obtained through calorimetric measurements. The model then encapsulates the CFS complexity by a two-layer approach. A method was also proposed to calculate the angularly resolved solar heat gain coefficients of systems composed of two subsystems.

In this contribution, we propose a global methodology to include the properties of the two subsystems in an extended version of the IFC standard description and a standard methodology to assess building’s performance.

KEYWORDS
Building Information Modeling, Building Energy Model, Complex Fenestration system, Thermal modeling, Industry Foundation Classes.

INTRODUCTION

Due to buildings' high energy demand, more and more buildings are designed toward high energy efficiency. Different parts of the building impacts its energy demand. Facades are the ultimate interface between the building's interior and outer environment, and therefore play a key role in the energy consumption. Energy efficiency in regard of the façade solution usually involves the building's energy demand, daylighting and glare problematics. This question is addressed early in the planning phase, and needs complex simulations to be performed. Those simulations are often addressed to experts in building's energy consumption.

For such simulation to be performed, multiple data is needed for a correct modelling of the façade's impact. It's usually required a representation of the building's geometry, the thermal properties of its opaque materials (walls, slabs…) and detailed information about the fenestration's system (window + shading device) to describe its optical and thermal behavior.

The geometry creation of the building energy model faces actually many problems. When it is natively supported by the building design software, it is sometimes subject to versioning problems. Some softwares stop supporting energy simulation programs, or require an old version of it. When the building energy model is not natively supported, then its creation is a complex and time consuming task, as it requires a manual recreation by the engineer, and it's also subject to comprehension errors and inadvertency mistakes (for example: creation of a building energy model from an architect floor plan).

The product data model of the fenestration system also faces some communication problems. It is not unusual that the manufacturer provides insufficient data to handle the system's complexity. The engineers have then to contact back the manufacturer and ask for data. The data may sometimes not even be available and requires new measurements. This whole process may induce a noticeable delay in the building process.

To solve those recurrent problems, Building Information Modeling (BIM) is foreseen to provide a definitive answer. BIM is the modeling of the whole construction process, and the answer of industry to data's fragmentation in different technologies. It aims to provide one dataset reusable in every aspect of a building's life cycle, from the management and coordination of the different construction partners to the dismantling of the building. BIM's philosophy fully includes energy problematics but no energy simulation tool offers full BIM support currently. One of the best supported BIM formats is actually the Industry Foundation Classes (IFC) developed by BuildingSmart. Some efforts have been devoted towards recreation of a building energy model (WoonSeong et al. 2016, Rose et al. 2015, Giannakis et al. 2015). These works lack an advanced and standard modelling of complex fenestration systems (CFS).

The purpose of this paper is to propose a methodology for a more accurate modelling of complex fenestration systems coupled with IFC. It aims to provide a standardized and automated workflow for building energy efficiency in regards of facades' solutions. A new methodology will be presented to create from IFC a building energy model that efficiently combines daylighting and thermal simulations based on ray-tracing that should be suitable for most of the buildings.

METHODOLOGY

Overview of the global methodology

Our research primarily focuses on a standardized methodology to evaluate the window's performance within Building Information Modelling. A typical performance evaluation of a window usually implies the evaluation of its performance in one or multiple template rooms.

Our methodology relies on two independent phases that extract building's skeleton from the BIM and incorporate an accurate thermal model to IFC:

Phase 1: Geometrical extraction

- Transform IFC's parametric geometry to explicit geometry
- Use a "Binary Space Partitioning Tree" for space partitioning, with boundary surfaces as walls, floor, roof, ceilings and slabs.
- Extract rooms of building that have at least one window (may be improved to extract larger zones instead of single rooms)
- Distinguish template rooms (rooms that behave in the same way: have very similar geometry, orientation and windows with same optical/thermal properties)
- Simplification of the geometry
- Recreation of missing information
- Translate to simulation engine's format

Phase 2: Product Data Model

- Develop an *IfcPropertySetDefinition* that would carry the thermal/optical model specifications. The choice of these models will be detailed later.
- Share simulation results within IFC

The presented work in this paper relies on a developed program to transform a BIM's geometry to explicit geometry suitable for the simulation program. It will propose a standardized methodology to carry optical and thermal model to handle most CFS. The intended BEM relies on the use of the 3-phase method for ray-tracing and is further coupled with the Blackbox Model (Kuhn 2011) to accurately model the energy gain from the CFS.

Daylighting calculation

The daylighting calculation should take into account BIM's rich capability for an accurate modelling that doesn't only calculate the overall illuminance in the room, but also its distribution. Those simulations should also be fast, because BIM is an evolving model through the construction process, simulations may need to be redone multiple times to take into account the different changes in the building. And finally the simulation methodologies should be able to cover most of building cases. Thus the need of a methodology that combines accuracy and speed and that can be generalized to most complex fenestration systems.

Currently multiple techniques have been proposed, the most used ones are ray-tracing and radiosity. Heckbert (1990) proposed a classification based on lights path for illuminance calculation methodologies. It has been further extended by Veach (1997):

Radiosity (Moon 1936): is a fast algorithm to calculate global illumination. It is classified as LD^*E which means it supports an indefinite number of lambertian surfaces. It only handles diffuse reflections.

Ray-tracing: is a slower but more accurate algorithm that aims to accurately calculate the illuminance. RADIANCE's backward ray-tracing approach (Ward et al. 1987) based on Whitted's algorithm (1980) is *L(D|G) [S*]E*. In summary it means that it supports lambertian, glossy and specular reflection.

From these classifications, radiosity is demonstrated to not being accurate enough in multiple cases, especially in case of buildings with complex geometry or original architecture (while being suitable for most simple rooms and work offices). Those complex cases are important in BIM's philosophy. Moreover some experiments (Tsangrassoulis et al. 2013) further assert that it is not suitable for energy savings simulations due to Daylight. Radiosity cannot therefore be used as a general and standard approach.

The ray-tracing methodology offers those capabilities but is slow, and faces another problem in case of some advanced complex fenestration systems: it may be very difficult to give a detailed description of the CFS geometry and the full optical properties of each surface, which may be problematic for BIM's philosophy that tries to comprehend most cases and standardize communications.

To work around the speed problem of ray-tracing and the difficulty of modelling a CFS, the three-phase method (Ward et al. 2011) has been developed. It offers a good calculation speed combined with sufficient accuracy for most cases (Bueno et al. 2015) with the use of Bi-directional Scattering Distribution Function (Klems 1994) as proxy geometry to represent the CFS. The BSDF can be calculated in some cases (as venetian blinds) or can be experimentally measured.

The 3-phase method relies on a division of the calculation into 3 matrices (calculated by ray-tracing in RADIANCE), while partitioning the sky and window into patches, and the building surfaces into points named "sensors". The 3 matrices are:

- Daylight matrix *(D)* describing the effect of sky patches, as defined by Reinhart or Tregenza, on the window patches.
- Transmission matrix *(T)* which uses the BSDF.
- View matrix *(V)* describing the relation between the discretized window and the walls' sensors.

The illuminance calculation is done by:

$$I = VTDs \qquad (1)$$

Where s is a vector describing the luminance of each sky patch (including the sun).

The calculation of the T matrix relies internally on the use of a BSDF. The BSDF will serve as an optical model of the window and its recreation in IFC will be discussed in a later chapter.

The view matrix relies on a prior discretization of the wall into small patches described by their centroids (called usually sensors) and weighted by their surface. The creation of those patches may use computational geometry techniques for mesh subdivision as regular grid, tessellation, triangulation, etc...

The main advantage of this methodology is to permit a fast calculation combined with sufficient accuracy and easy modelling for most daylighting calculations. This methodology needs a correct representation of BSDF in IFC, some geometric processing of the room's geometry. Moreover to it should be coupled with thermal simulations to evaluate the energy demand of a building.

Irradiance calculation

Irradiance calculation is very similar to daylighting calculation in its algorithms. It faces then the same problems as described before. Radiosity does not offer sufficient accuracy for the building's energy demand.

Moreover in some cases an irradiance flux distribution may be necessary for other problematics as thermal comfort, or to answer some problems of specific buildings as, for example, museums where high irradiance should be avoided for some work of arts.

Ray-tracing faces the same problems as described above, and this is why the choice of the 3-phase method as an accurate, easy to implement and fast calculation methodology is suitable for irradiance calculation as well. In addition to the 3-phase method, we will need a thermal model that describes the energetic behavior of the window.

Thermal model

The Blackbox model (Kuhn et al. 2011) is a model that describes complex fenestration systems (glazing + blind) with a simpler two-layer system. It aims to provide a model usable in most simulation programs that relies on measured calorimetric data, or in some cases calculated, to represent the thermal behavior of a complex fenestration system. It is a work around to the problem of recent and complex fenestration systems that may not be possibly represented within current simulation program models, or inaccuracy problems with systems that deviates a lot from their ideal design.

The use of a semi-empirical model leads to an easy and computationally light model to use in energy simulation programs without sacrificing accuracy for most complex fenestration systems.

In this model, each layer is characterized by an angular solar absorbance and the two are separated by a thermal resistance. It relies on some measured and/or calculated data as input:

- Angular g-value: measured with specific external and internal resistances.
- U-value: measured with the same external and internal resistances.
- Angular transmittance
- Angular reflectance (optional): to calculate the temperature of the external surface.

It is demonstrated that with this input the following absorbances can be calculated:

$$\alpha_{inner\ layer} = \frac{q_{tot}(R'_e + R'_s[T'_{mean}] + R'_i) - \propto R'_e}{R'_s[T_{mean}]} \tag{2}$$

$$\alpha_{outer\ layer} = \frac{q_{tot}(R'_e + R'_s[T'_{mean}] + R'_i) - \propto R'_e}{R'_s[T_{mean}]} \tag{3}$$

The Blackbox Model is then coupled with the 3-phase method in a simulation engine to simulate the radiative flux on the walls. This approach leads to an accurate representation of the transmitted irradiance distribution in the room.

We will now describe a workflow to automate its use with IFC.

Data processing from IFC

IFC format can store geometry data in explicit and parametric format. Moreover, it stores objectified relationships for some spatial relations like creating a hole inside a wall. Simulation programs often need to use an explicit geometry of meshes (usually polygons with every vertex coordinates defined). Thus a transformation from parametric equations to explicit geometry is required as first step. It is done with a newly developed geometry library that supports all IFC's primitives. It is then possible to transform it into a Building Energy Model.

We will then have to link it to the input of our Blackbox Model. Integrating it within IFC is described in the next chapter.

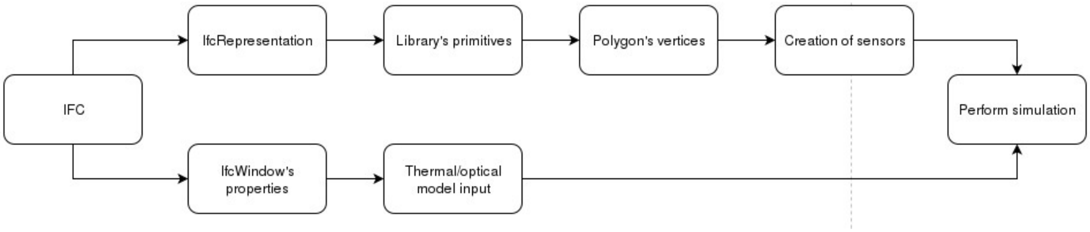

Figure 1 : Representation of the workflow from IFC to building performance simulation

Product Data Model in IFC

As seen in the Blackbox model description, a complex fenestration system needs 3 types of inputs to be fully described. IFC format supports g-value, U-value and the solar transmittance, but does not natively support angular dependencies. It offers some means to support those kinds of values through its complex properties named IfcComplexProperty.

This complex property enables to hold multiple properties (simple or complex) in it. It makes possible to describe in the same property the parametric ranges of angles, and the values as a list of data.

The description of a BSDF can be done with a "tree" made of multiple "IfcComplexProperty". This tree can virtually carry any angle or wavelength dependent data. The first level of nodes describes incident wavelength ranges, the second level the incident patch (subdivision of space), the third level the reflected/transmitted wavelength ranges, the fourth level the reflected/transmitted patch, and then the leafs can contain data such as transmittance or reflectance.

Property set definitions are schemas intended to extend IFC's property capabilities based on regional or project agreement. They are shared in *xsd* format, following the xml standard.

There is already a standard property set definition covering thermal and optical representation of glazing systems called, but is unsuited for the BlackBox model as it does not offer any angular dependent data.

We will create our own *IfcPropertySetDefinition* for this research that will be able to handle all of our requirements. It would hold 3 IfcProperty that describe the needed input. Then we will associate it with a window. This association will be done manually, but will be automated in further development.

The support of this IfcPropertySetDefinition required an additional development in our IFC parser as it is not natively present in IFC. It was then combined with the geometrical processing described earlier to get the fundamental input and the automated creation of our building energy model.

CONCLUSION:

The presented work presents a methodology to accurately evaluate the daylighting and thermal gains of a complex fenestration system from a BIM. It tries to standardize and automatize this whole process to make the study of the energy efficiency of a building in regard of facade solution easier between project partners and avoid some communication and technical problems that may arise later in the building process.

Some questions are still left open though. Which simulation results need to be incorporated in BIM? What changes in the building may change those results, or may even change the inputs of the model? BIM is a dynamic model that evolves in time and BEM should not be viewed as a static model only. Moreover, with the newly developed methodologies that automatize the BIM to BEM transition; it is important to rethink about the simplifications of the building's geometry that are currently made in order to speed up the modelling and simulation and see how they can take advantage from BIM capabilities and how they can be normalized.

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