DISCLAIMER

For review only - Simulation of complex glazing products; from optical data measurements to model based predictive controls.

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1 ABSTRACT

Complex glazing systems such as venetian blinds, fritted glass and woven shades require more detailed optical and thermal input data for their components than specular non light-redirecting glazing systems. Various methods for measuring these data sets are described in this paper. These data sets are used in multiple simulation tools to model the thermal and optical properties of complex glazing systems. The output from these tools can be used to generate simplified rating values or as an input to other simulation tools such as whole building annual energy programs, or lighting analysis tools. I also describe some of the challenges of creating a rating system for these products and which factors affect this rating. A potential future direction of simulation and building operations is model based predictive controls, where detailed computer models are run in real-time, receiving data for an actual building and providing control input to building elements such as shades.

2 INTRODUCTION

Windows in buildings and homes are responsible for about 4% of the total annual energy consumption in the US (Apte 2006). This energy consumption is related to heating, cooling and lighting in homes, offices and other buildings. Buildings are subject to continuously changing climatic (exterior) conditions such as solar radiation, wind and air temperature. Requirements for the interior climate of a building are usually static and only vary slightly throughout the year or day (daytime/nighttime mode). Windows and the rest of the building envelope are the separation between these two environments. A static window (a window that has properties that do not change) cannot respond to changes in the outside conditions. Equipment that provides heating, air conditioning and ventilation is currently the only other variable component that can help create this stable interior climate.

Windows with operable shading devices can help by making the window dynamic and responsive to the environment. The energy consumption associated with static windows can also be reduced by incorporating optically complex systems, which for example can admit light only at certain angles, rejecting light at other angles.

Computer simulation can be used to predict how much energy a building will use. Various annual energy simulation tools (EnergyPlus 2011, DOE2 2000) are

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widely used for this purpose. The increased use of shading devices such as roller shades, venetian blinds, cellular shades and light shelves poses a challenge for accurate simulations. As will be described below, these devices have complex angular properties that require special equipment to measure as well as the development of new models to simulate their performance. Many of these products are dynamic in that they can be deployed by automatic or manual systems. This paper describes various approaches to measuring the optical data and the variety of computer simulation tools that this data can be used in to calculate their contribution or reduction of building energy use. The measurement of thermal properties such as emittance and thermal conductance are not discussed in this paper.

3 METHODS FOR MEASURING OPTICAL DATA

There are many laboratories worldwide that can measure specular samples such as clear glass with or without coatings and provide spectral data on transmission and reflection. No angular measurements other then normal-incidence are needed since these products are not light redirecting. The angular properties of these glazings can be calculated fairly accurately from equations (Karlsson 2000). Every few years an Inter Laboratory Comparisons (ILC) is held, where various laboratories measure a number of identical samples. The results are analyzed by an independent organization and any lab whose data is out of the accepted tolerance bands will receive assistance in order to improve their measurements. A database with spectral data for thousands of glass layers is publicly available (IGDB 2011)

Many shading devices (fabric shades, venetian blind slats etc) are light redirecting and/or diffusing. For most products this means that the angular properties have to be measured in addition to the spectral transmittance and reflectance because it is very difficult to predict these properties for the wide variety of shades.

A standard way to describe angular properties of a layer or a system is a Bi-Directional Scattering Distribution Function (BSDF). A BSDF is a general mathematical function that describes the way in which the light is scattered by a surface. A BSDF is a combination of 2 Bi-directional Transmittance Distributions Functions (BTDFs) and 2 Bi-directional Reflectance Distribution Functions (BRDFs). There are 2 BTDFs and 2 BRDFs because to fully characterize a layer, material or system we need to characterize both sides of a layer. The BSDF describes how light coming from a certain direction is transmitted and reflected in other directions. These directions are obtained by discretizeing a hemisphere into patches using an angular basis. A commonly used basis in the windows and daylighting area is the Klems basis (Mitchell 2008) which divides a hemisphere into 145 patches. This results in a matrix of 145 incoming by 145 outgoing directions.

There are various methods to measure the optical properties for complex glazing and shading devices. Some of the measurements are the same ones used for specular glazings.

3.1 **Spectrophotometer**

The spectrophotometer is the device used for most specular glass measurements. In this default mode the device measures normal incidence transmittance and reflectance of non light-redirecting products. This device can provide spectral measurements in the range of 300 nm - 2500 nm, at a resolution of around 1 nm.

With the addition of a small (0.05 - 0.15 m) integrating sphere, this device can also measure the reflectance of diffuse samples like painted venetian blind slats. The only requirement is that the samples are flat, which can be achieved by gluing the slats to a flat substrate, or contacting the manufacturer for non-curved slats. This setup can also be used to measure the diffuse reflectance of diffusing glazing materials such as fritted glass. For fritted glass two measurements are performed, one that measures only the direct (ie non diffuse) transmittance, and a second measurement that only contains the diffuse transmittance (excluding the direct component). The measurements are performed on fully covered (100% coverage) frit samples. The specular transmittance and reflectance for the substrate (0% coverage) are also measured.

Measuring the diffuse transmittance of materials is more challenging, but can be performed with a spectrophotometer for certain materials. The main limitation is the thickness of the sample. Thick (>0.006 m) diffusely scattering samples cannot be measured accurately because the integrating sphere does not capture some of the light.

All the previously described methods only provide data for normal incident direction illumination. The University of Waterloo (Kotey 2009) developed a method to measure off-angle properties in a spectrophotometer. The method uses a series of fixed angle tubular insets that can be placed inside the integrating sphere of the spectrophotometer. This can provide additional off-normal angular measurements. The method described in (Kotey 2009) produces data for 6 addition off-angle measurements. Opaque samples can be measured in an integrating sphere by using a center-mount approach, but this method fails for translucent samples (Edwards 1961)

3.2 **Goniophotometer**

The spectrophotometer described above is a bench top device. Most goniophotometers however are room-sized devices. The device installed at Lawrence Berkeley National Laboratory has a fixed light source, with a moving sample holder and detector. It uses a finite set of incident angles (10-20), and measures many thousands of outgoing angles for each incident angle. The device has a fixed number of detectors that can measure spectral response;

commonly 3 visible and 1 near IR sensors are used. This device has a much lower spectral resolution then the spectrophotometer but a much greater angular resolution. The high-resolution angular output can be used to generate detailed bi-directional transmittance and reflectance data.

3.3 Ray-tracing

Computer based ray-tracing is not a measurement technique, but can be used with some of the devices mentioned before to create a spectral and angular data set describing a complex diffuse or light redirecting device. Users create a geometrical representation of the device or system in a ray-tracing program and then assign optical properties to the materials. To ray-trace a curved venetian blind system, one would measure the reflectance of the slat material in a spectrophotometer, and then assign that to a surface in the ray-tracing tool. The ray-tracing tool will create thousands (or millions) of imaginary light rays, illuminate the sample, and track where the rays go. The output from these tools can be a bi-directional scattering distribution function (BSDF) that can be used in other programs described later in this paper. There are commercial tools available that cost >$10,000, but there is also a recently developed model called genBSDF in the open-source Radiance ray-tracing program.

4 STORING AND EXCHANGING OPTICAL DATA

A file format was developed by LBNL to store the BSDF data. The file is an Extensible Markup Language (XML) open format file, which provides great flexibility for expanding the file with additional information. The Radiance genBSDF tool for example can store the geometry of a blind in the XML file in addition to the BSDF optical data. This file format is currently being generated and read by a few tools (Radiance, WINDOW6 and a commercial ray-tracing program). The file can store BSDF's at various bases and spectral resolutions, although not all tools support all the options.

This XML file format is intended to be use to describe both shading layers (such as a venetian blind, or a fritted piece of glass) as well as complete systems (like 2 pieces of glass with a roller shade in between). It is an input format to some programs, and an output format for others. Currently the XML file stores the optical data for one state or configuration of the product. Products that have variable properties, like venetian blinds (varying slat angle) or electrochromic glazings (varying tint level) could potentially store multiple states of the product in one XML file.

A Complex Glazing DataBase (CGDB) format is being developed that can act as a repository for all these individual BSDF XML files. This database can also store additional thermal information such as thermal emittance that might not be present in the BSDF XML file. The database would consist of peer-reviewed data for shading layers and complex glazing layers. The peer review process is similar to the International Glazing DataBase (IGDB) where every person or institution who submits data to the IGDB automatically becomes part of the peer-review group. The peer-review group also contains experts from universities and government institutions worldwide that might not submit data, but review the data as part of the peer-review process.

The current IGDB contains spectral data for almost 4,000 specular layers (glass, laminates and films). It is expected that the CGDB will also become quite large, because many shade manufacturers offer a wide range of colors for their shades. Sometimes these products are referred to as window fashion.

5 TOOLS

There are a number of tools that can be used in the analysis of complex glazing systems and shades.

5.1 WINDOW

The WINDOW6 program is developed by Lawrence Berkeley National Laboratory and is an extension of the WINDOW5 program. The WINDOW5 program only deals with specular glazings and is used by the National Fenestration Rating Council (NFRC) for determining U-factor, Solar Heat Gain Coefficient (SHGC) and Visibile Transmittance (VT) for windows. All these properties are determined only at normal incidence. WINDOW6 allows for the modeling of complex glazing products and provides detailed angular output, it also can calculate performance for specular products.

The optical calculation for complex glazing products are based on an ASHRAE research project by Joe Klems of LBNL (Klems 1994a, 1994b). The result of this research project was a ‘matrix multiplication method’ where every layer in a multi-layer system is represented by a BSDF matrix. To derive the properties for the whole system, these matrices are multiplied. The result is again a BSDF matrix, but this time for the whole system.

The method relies on these matrices being square, which requires the same set of incident and outgoing angles. The default in WINDOW6 is to use the Klems basis that consists of 145 incoming directions and 145 outgoing directions. These bi-directional calculation in WINDOW6 can sometimes take significant time (multiple minutes), for this reason there are also half (73 * 73) and quarter size (41 * 41) bases available in WINDOW6. These bases are derived from the Klems basis, but utilize larger patches for dividing the hemisphere. All these bases are stored in a separate XML file, and can be modified by the user.

WINDOW6 has a number of built-in analytical models that can generate these bi-directional matrices from simplified input parameters. Models are available for the following products:

- Venetian Blinds. The geometrical input parameters for the venetian blind model are slat width, slat angle, slat thickness, curvature and slat spacing.

The optical properties for a flat slat sample can be measured with a standard spectrophotometer. The geometric parameters in combination with the optical properties are used in the program to generate a bi-directional matrix describing the venetian blind layer (Curcija 2006a). This matrix is generated automatically when a user performs a calculation.

- Fritted glass. Ceramic frits can be applied to glass to create a diffusing or coloring effect. Most of the frits are translucent. Various patterns such as dots, stripes etc create a pattern on the glass, which can be represented by a coverage percentage. As described above in the measurement section, the optical properties for these frits are measured on samples with 100% coverage and 0% coverage. The program creates a bi-directional matrix from the frit coverage percentage and the optical data for the fritted and clear glass. This model assumes that the diffuse portion of the frit is hemispherical diffusing. Another option is measure the frit in the goniophotometer and use the measured BSDF data rather then this frit model.
- Woven Shades and Insect screens. This model is based on the assumptions that woven fabrics and insect screens have a simple regular pattern and a constant thread diameter. The geometric inputs to this model are thread spacing and thread diameter. The optical input is the thread reflectance. This can be measured in the spectrophotometer by either obtaining a solid sheet of the thread material from the manufacturer, or folding the sample over multiple times, which creates a close approximation of a solid sheet. Joe Klems and Ross McCluney developed this model (Curcija 2006b). Certain fabrics do not have a simple regular pattern, for example by having different horizontal and vertical thread spacing. These samples can be measured or ray-traced with the other methods described previously and used in the program directly as a BSDF without using this analytical model.
- Specular glass. Specular glass and clear plastics have no scattering properties and generally have well known angular responses. A bi-directional matrix of the specular layer needs to be created if a specular layer is used in combination with diffusing or light redirecting layers. These layers will result in a bi-directional matrix with only the elements on the diagonal populated. All elements on the diagonal have the same incoming and outgoing angle, which is the definition of a non light-redirecting specular layer. Since glass is axi-symmetric (rotational symmetry) the values on the diagonal vary only by the profile angle. All these calculations are performed by WINDOW6 and are completely hidden from the user.

WINDOW6 currently provides output for specular glazings to EnergyPlus. A link for complex glazing output from WINDOW6 is under development. Figure 1 shows how WINDOW6 is connected to the other parts of this workflow.

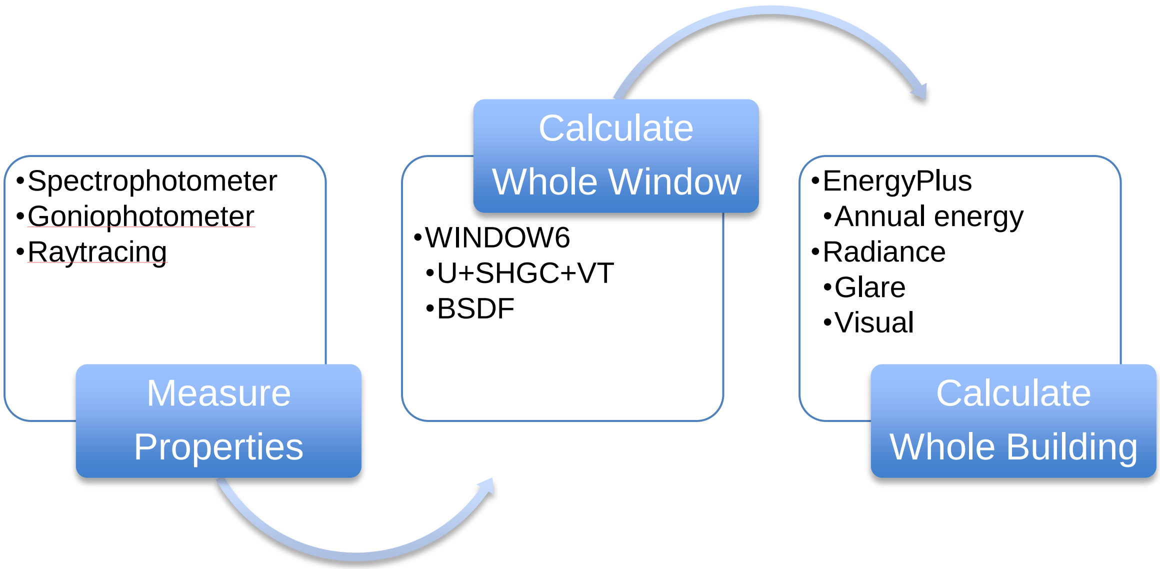

Figure 1 – Workflow between various software tools

5.2 Radiance

Radiance is a ray-tracing tool that traditionally has been used to simulate the light distribution in environment. It is a physically based renderer which results in highly accurate simulations. It can predict the light levels and distribution of light in a space in response to multiple light sources (sky, sun, electric lights etc). It has been successfully used in very complex spaces, with many light sources, with rendering calculation times of several days. Up to recently it was not able to model complex glazing systems with bi-direction input data. Radiance is a backwards ray-tracer, which means it starts from a certain location (like a point on a desk in a room), and sends out rays in all directions, trying to find light sources. This approach works well with a specular window, but has shortcomings with light redirecting shading devices such as curved venetian blind slats, that allow no direct view of the sky, but still allow significant amounts of light to enter a space. Several improvements to Radiance over the last few years now allow Radiance to use BSDF descriptions of windows and perform accurate and much faster calculations of spaces that are illuminated through complex fenestration systems. Particularly the 3-phase method as described in (Ward 2011) shows great potential for these kinds of simulations. Radiance can directly read the XML BSDF files that were described earlier in this paper.

An exciting new addition to Radiance is the genBSDF module that can generate a XML BSDF file from a radiance model of a complex glazing. This tool uses the Radiance ray-tracing engine but rather then simulating a room, it only calculates how light travels through a complex glazing element. An example from the Radiance documentation shows how to generate a XML BSDF file for a venetian blind. Only two commands are needed:

```
genblinds blind_white blind1 .07 3 1.5 30 40 | xform -rz -90 -rx 90 >blind1.rad
genBSDF  -r  @rtc.opt  blind_white.mat   glazing.rad   blind1.rad   >blind1.xml
```

This however also shows the level of expertise needed to use these tools. There is no graphical user interface (GUI) within the Radiance tools. There are however other programs that have GUI's and use Radiance for calculation (such as WINDOW6 and COMFEN).

Radiance can both provide input to WINDOW6 (genBSDF) and use the WINDOW6 output (BSDF for the whole system).

5.3 COMFEN

COMFEN is a graphical tool targeted at architects and engineers. It can be used to determine the impact of various glazing systems, shading systems and facade layouts on energy consumption in commercial buildings. It models a perimeter office or room as a single zone model, since this is where the facade, windows and shading have the largest effect on energy and comfort. The core and auxiliary spaces of a building are ignored. COMFEN allows side-by-side comparisons of different configurations, such as orientation, shading devices like blinds, fins and overhangs, and glazing options. COMFEN links to the following tools for its calculations.

- EnergyPlus is used for annual energy calculations and provides detailed reports on energy consumption, peak energy used, carbon emissions, thermal comfort. This includes orientation specific output.
- WINDOW6 provides glazing system performance numbers (U, SHGC, VT) and bi-directional optical data for shading systems
- Radiance creates images that show the light distribution in a room, providing a visual method to compare different window configurations.

Links to advanced thermal comfort models and cost estimators are currently under development.

5.4 ASHWAT

An ASHRAE sponsored research project (RP-1311) titled " Improving Load Calculations For Fenestrations with Shading Devices" was completed in 2009. The University of Waterloo and Chip Barnaby performed the research. The outcome of the research project was a set of Fortran algorithms and simplified tables for the ASHRAE Handbook of Fundamentals. The model was designed to be very fast, because it is used in annual calculations and may be called thousands of times during a simulation.

A core component is the equivalent layer model, which reduces every layer in the model to a basic set of optical and thermal indices. The optical transmittance of a layer is characterized by 12 solar properties as opposed to 145*145*2*2=84,100 values for the full BSDF characterization (Incoming Basis * Outgoing Basis * front&back * transmittance&reflectance) used in other tools. This creates a large speed increase. Optical models for various shading devices such as drapes, woven shades and venetian blinds have been developed.

The ASHWAT model is available in Fortran code free of charge from ASHRAE (Wright 2009)

6 RATING ISSUES

One way to characterize the general energy performance of complex fenestration systems is to create a rating for them. Ratings like these are not specific to a building or location but are generalized to facilitate comparison between products. Ratings have been quite successful in the window industry for windows with specular glazings. The National Fenestration Rating Council has been developing ratings for windows since the early ‘90s. The main performance indices that are rated are quite simple, U-factor to characterize thermal transmittance, solar heat gain coefficient (SHGC) to indicate how much solar energy is admitted and visible transmittance (VT) which relates to the amount of daylight transmitted by a window. Both SHGC and VT are determined at normal incidence. Everybody agrees that this situation is somewhat artificial, because for vertical glazing, the sun is never at normal incidence to the window, except right at sunrise and sunset. The angular transmittance of glass however does not vary much between normal incidence and incidence angles up to 50 degrees. For clear glass the reduction in transmittance at 50 degrees is only 5% compared to normal incidence. There are a few optional indices such as condensation resistance (CR) and air leakage (AL).

A straightforward approach would be to rate complex fenestration systems using the same normal incidence assumptions. Figure 2 shows a graph of visible transmittance for 2 different systems. One is a specular glazing system, the other a window with a venetian blind between the glass layers. As can be seen in the graph, the transmittance at normal incidence (profile angle=0) is identical (0.64) for both systems, but the transmittance at off-normal angles changes much more rapidly for the venetian blind glazing system. This shows the limitation of using a normal incidence only rating for non-specular systems like venetian blinds.

Current rating systems only consider the fully open (i.e. the state with the highest normal incidence solar and/or visible transmittance) and fully closed (the state with the lowest transmittance). These states are well defined and therefore unambiguous for creating rating numbers but they ignore control strategies and angular dependence.

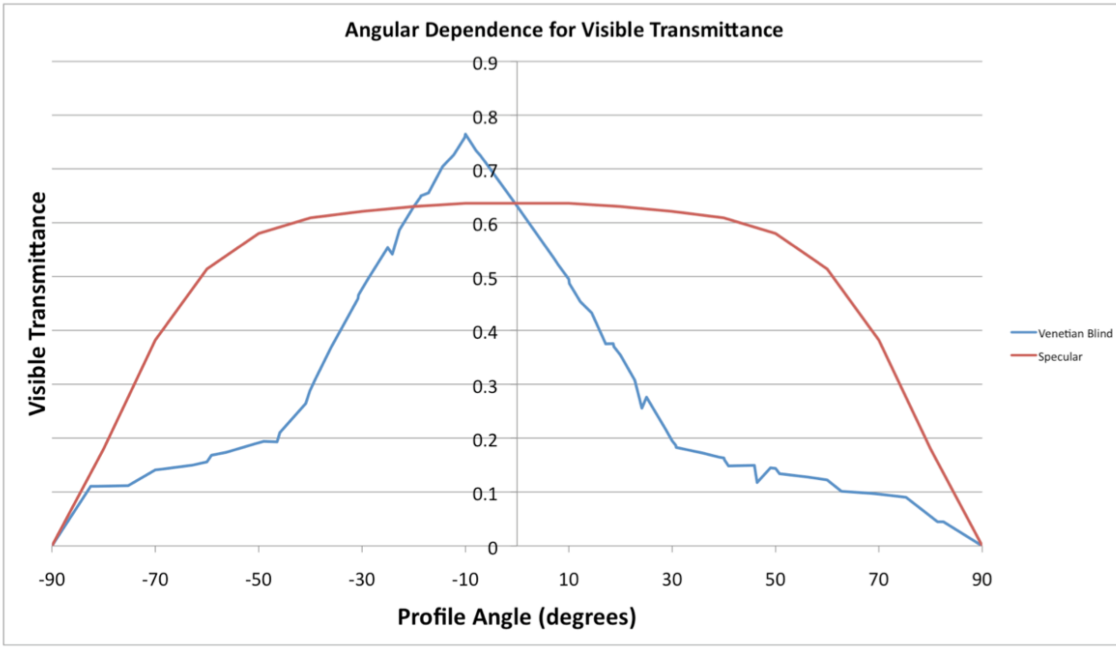

Figure 2 - Visible transmittance of a specular glazing and a glazing with a venetian blind. Note identical transmittance at normal incidence, but wide variation off-angle.

One of the challenges for creating energy rating systems for complex glazings is related to regional differences in solar position, and climatic conditions. A single nation-wide rating number will usually be for an average condition, ignoring regional effects. Another challenge is that many complex glazing-systems can have multiple states such as the slat angle of a venetian blind or partial deployment of a woven shade. To properly account for the full energy impact of these systems, an annual energy rating is needed. The control strategy for these complex glazing systems with multiple states will strongly affect their energy annual rating.

For manual systems the controls issue includes the challenge of predicting human behavior. For automated system the question becomes what the parameters are that influence the control decisions. Potential parameters are energy consumption, light level, thermal comfort or visual comfort (glare).

When the performance of a shading device (such as a venetian blind or roller shade) is rated it needs to be calculated in relation to a base window. The SHGC of a venetian blind next to a single clear glazing is quite different from the sample blind next to a double glazed low solar gain window. A base window or set of base windows needs to be carefully chosen to allow a relevant estimation of performance in a broad range of applications.

7 FUTURE DIRECTION

One exciting new development is in the area of Model based Predictive Controls (MbPC). Computer simulation models are linked together and used to predict the optimum state for a control point (such as shade position, light level etc). Traditional controls are usually fairly simple. A thermostat measures the temperature in a room, and turns on the heating or cooling based on the current temperature. The thermostat has no idea if the blinds are going to be raised or lowered in the near future.

Model based predictive controls can be used both to control objects in a real-word physical building and within simulation models as an advanced control strategy.

When MbPCs are used to control physical buildings the simulation programs will receive input parameters from the real world. Such inputs might be the weather conditions (solar radiation, temperature, wind speed etc), number of occupants in a space, lighting levels and shade position. Simulation programs such as Radiance could evaluate the occupant glare and lighting energy required to keep an office at a certain light level for various states of a roller shade that can block light from entering the space. At the same time the EnergyPlus program could perform an energy calculation to determine which configuration has the lowest energy use and the highest occupant comfort.

the software tools must run fast enough to enable real-time control. Certain control points might be adjusted every 5-15 minutes, which means that all the simulations have to be finished in time to provide a new control signal to the building. Modern multi-core computer usually have enough computing power to perform these calculations, but in complex situations an advanced computing cluster (multiple computers working in parallel) might be needed.

These advanced MbPC simulations can be performed during the development of new control algorithms. Usually the end goal is to find the optimum control algorithm, and then embed this in a controller that will be used to operate the building. It is unrealistic to expect the availability of a advanced computing cluster for the control of regular buildings.

At this point MbPC simulations are used for control in research facilities or by manufacturers to test or develop new control algorithms.

MbPC can also be used in a pure simulation environment without a physical building to control. Annual energy simulation tools like EnergyPlus currently have a fixed number of build-in control algorithms. Examples of these control algorithms for shading systems are:

- lower shade when there is direct sun on the window
- lower shade when there is a potential for glare in the space
- lower the shade if the system is in cooling mode

All these control algorithms are based on current or past value of variables or sensors. There is no knowledge of what will happen in the future or how it will affect future states of the model. in MbPC it is possible however to stop at a certain time step during an annual simulation, and try out a few different scenarios of control (marching forward in time) and pick the best one. This is comparable to a computer chess program that evaluates several scenarios for a certain number of moves into the future, and chooses the best next move. The benefit in simulation MbPC is that there is no unknown opponent that makes unpredictable moves.

Multiple simulation tools can be linked together, such as Radiance for (day)lighting, Modelica (Wetter 2009) (for complex HVAC modeling) and EnergyPlus for annual energy simulations. Combining these multiple simulation tools with the technique described above of trying several future scenarios results in a very powerful simulation environment. The building control virtual testbed (BCVTB 2011) tool is providing a rich generic framework that can allow users to build such complex models.

8 DISCUSSION

Some of the models and techniques described in this paper require significant time to learn and operate. Their use is feasible in a research environment or for project where there is an understanding of the benefits of extensive analysis. The level of detail that these tools can provide has improved significantly over the past few years, which requires more computing power to solve. Fortunately PC computing power is doubling every 1.5 years and the efficiency's to perform these calculations is also doubling every 1.5 years (Koomey 2011). This means it will take the same amount of energy (kWh) of computing power to perform twice as many calculations for ever more accurate and detailed simulations.

To achieve the potential in energy conservation and increased human comfort in all buildings the integration of these simulation tools has to be seamless to reduce the amount of human effort involved. A good connection with existing workflows (such as CAD programs and design practices) is also needed to increase efficiency of time for the practitioner. Mark Perepelitza from ZGF who also has a paper in this session at the BEST3 conference will describe more about how these tools are used in professional practice such as an architect's office.

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11 DISCLAIMER