

## DAYLIGHT1-2-3 – A STATE-OF-THE-ART DAYLIGHTING/ENERGY ANALYSIS SOFTWARE FOR INITIAL DESIGN INVESTIGATIONS

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### ABSTRACT

This paper provides an overview of Daylight1-2-3, a new daylighting/energy analysis software for design professionals and architectural students with an interest in daylighting and sustainable design, but no required previous knowledge of either daylighting concepts or simulations. The initial version of Daylight 1-2-3 focuses on private offices, open-plan offices, and classrooms. The paper describes the process that the tool's development team went through to develop a common vision and requirement catalogue for Daylight 1-2-3 using both lessons learnt from previous software projects, as well as results from an online survey of mostly LEED Accredited Professionals. The requirement catalogue later helped the team to assemble a fast, state-of-the-art simulation engine: during a Daylight 1-2-3 simulation Radiance-based daylight coefficients are read into a customized version of ESP-r. The version has been specifically tuned to model occupant behavior (SHOCC module), calculate the latest generation of dynamic, climate-based daylight performance metrics (DDS module), and run an annual fully integrated lighting/thermal simulation in about a minute. Venetian blinds are modeled through SkyVision correction factors.

### KEYWORDS

daylighting, Radiance/Daysim, ESP-r, SkyVision, Lightswitch/SHOCC

### INTRODUCTION

This paper presents an overview of Daylight1-2-3, a new daylighting/energy analysis software. Developing a new design tool is an undertaking that requires a substantial amount of financial and human resources. In order to justify these expenses, clear criteria regarding the functionality, scope, and intended role of the tool in the design process have to be established early on in the development cycle. Some criteria are self-evident, e.g. the tool has to yield *reliable, consistent* results. If the tool is to attract a reasonable number of users it must further

provide information that is *relevant* enough to justify the users' time and *unique* in the sense that no other tool can provide them with less effort.

Building on lessons learnt from previous software projects, the Daylight 1-2-3 development team initially went through a rigorous exercise of understanding the strengths and weaknesses of existing tools, defining a target user group for Daylight 1-2-3, understanding the needs of this group through an online survey, and finally developing a strategy to meet these needs. This initial planning process is sketched out in the following section. The technical solutions chosen and models developed are described later in the paper followed by a fictional case study that illustrates how the tool can be used to inform various design decisions.

### LIST OF REQUIREMENTS

#### **'Relevant and Unique'**

A visit to the Building Energy Software Tools Directory (US-DOE 2007) in January 2007 listed 35 tools under the 'Lighting Systems' category, 21 of which were advertising daylighting as a key feature. Incidentally, three of these tools, Daysim, Skyvision, and Lightswitch Wizard were previously developed by the authors of this paper. Daysim and Skyvision are both 'expert' tools. The former is based on the Radiance raytracer (Ward and Shakespeare 1998) and provides annual daylight illuminance profiles and resulting electric lighting energy use in arbitrarily complex buildings (Daysim 2007). Skyvision was developed for skylight manufacturers and specialized consultants, providing information on optical and thermal properties of various skylighting systems combined with a variety of shading devices (Skyvision 2007). Lightswitch Wizard is a lightweight, online version of Daysim that was introduced in the summer of 2003 (Reinhart et al. 2003). The wizard provides daylight factor and daylight autonomy distributions as well as lighting energy use in private offices and classrooms and was mainly developed to make

Daysim's advanced daylight simulation concepts available to design professionals and architectural students with an interest in daylighting and sustainable design, but no required previous knowledge of either daylighting concepts or simulations.

The intent for the new Daylight 1-2-3 tool is to supersede and move beyond the Lightswitch Wizard. The tool targets the same user group as Lightswitch Wizard but expands the wizard's original scope by offering more holistic design advice as far as daylighting and energy are concerned.

At the beginning of the Daylight 1-2-3 development project the first step towards defining a requirement catalogue for the tool was to evaluate in how far the Lightswitch Wizard had managed to attract the target user group of non-specialist designers. Since the wizard is an online tool and users remain anonymous, the only thing known about its usage was the number of simulation sessions run which had been averaging a round 450 per month since January 2005. These numbers confirmed a strong interest in daylighting among design professionals and a high acceptance rate for online tools. But – according to the wizard's web statistics – only 15% of all visitors used the tool more than once and only 6% returned more than twice. This sobering finding indicated to the Daylight 1-2-3 development team that the wizard addressed the right content matter but failed to provide the information in an effective manner for design.

Some informal feedback suggested that some users only had a vague understanding of what they were simulating and accordingly how they could use Lightswitch Wizard results. The development team therefore decided to make the Daylight 1-2-3 GUI more visual than the Lightswitch Wizard GUI and to provide more guidance through help files and tutorials. In order to make Daylight 1-2-3 suitable for initial design investigations the GUI further had to remain easy to navigate even on an infrequent basis (once every couple of weeks), and simulation times had to stay at around a minute.

As described under the technical solutions section below, these ambitious, short simulation times convinced the development team that Daylight 1-2-3 would require an online component, i.e. at least part of the simulation engine would have to reside on a central server and be accessed during a simulation run via the internet. A key lesson from the Lightswitch Wizard project was that providing an online service can be challenging, especially if the simulations are piped through an already popular web server. For the wizard these challenges had sometimes led to stability issues, i.e. the

simulation service was either temporarily not available or even failed when server traffic was high. To reduce the risk of simulation delays Daylight 1-2-3 would reside on its own, dedicated web server. In order to ensure that Daylight 1-2-3 users would have permanent access to their simulation results the tool would further store the results on the user's computer.

Finally, Daylight 1-2-3 was to offer a large selection of façade designs and report energy use for heating, lighting, and cooling.

### **Online Survey**

In order to learn more about current daylighting design practice an online survey on the 'role of daylighting in sustainable design' was carried out during the summer of 2005 (Galasiu and Reinhart 2007). The survey was widely disseminated among design practitioners including members of the Canadian Green Building Council and the Royal Canadian Institute of Architects. 177 individuals participated in the survey. Notably, over 80% of them stated that they were either LEED Accredited Professionals or used LEED during their projects. LEED stands for Leadership in Energy and Environmental Design and is a green building rating system whose popularity and use among design teams have been steadily rising in recent years in the United States and Canada (USGBC 2007). The survey confirmed previous findings that 'experience from previous work' and 'rules of thumb' were the most widely used 'tools' for daylighting during the initial design phase whereas 'computer simulation' was the most widely used tool during design development. Another interesting finding from the survey was that open-plan offices, classrooms, and private offices (in that order) were the space types which participants reported to be most 'relevant to their work' and in which they believed 'daylighting to have the largest energy saving potential'. Based on these survey results the development team decided to initially offer these three space types in Daylight 1-2-3.

### **Simulation Output**

Once the user group and overall handling requirements for Daylight 1-2-3 were established the development team had to decide what performance metrics the tool should report. The objective was to provide relevant information on daylighting and overall energy use. While monthly energy use patterns were an obvious choice to compare the energy implications of different daylighting designs, when it came to the non-energy aspects of daylighting the choice of metric and how to apply them was less clear. Daylight factor, interior illuminances under selected sunny sky conditions, as well as solar ingress studies are

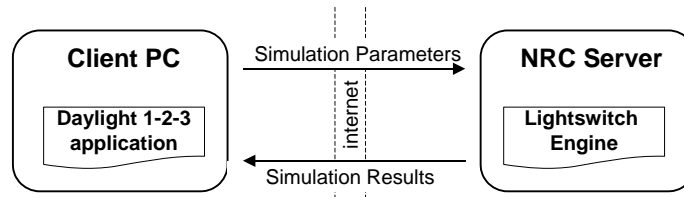


Figure 1 Daylight 1-2-3 is a Client-Server Application.

performance metrics that are already offered by a number of software packages. The daylight factor (and more recently the glazing factor) is an especially popular metric since it is referenced by the LEED rating system credit 8.1 (USGBC 2007). All of these daylight performance metrics have in common that they are ‘static’, i.e. they are based on a single sky condition: an overcast CIE sky in the case of the daylight factor. In contrast a ‘dynamic’, or ‘climate-based’ daylighting metric considers all possible sky conditions at a building site throughout the year. Recent research examined the limitations of static metrics suggesting that climate-based metrics can provide superior design advice (Reinhart et al. 2006). While it will take time to convince designers to switch from the daylight factor – a metric that has been used for close to a century – to a new set of metrics, the number of voices promoting, and practitioners using, climate-based metrics is growing. Remaining barriers towards their wider usage are that (a) calculating these metrics currently requires advanced simulation skills and (b) no consensus has been reached as to which of the new metrics to use and what target levels to apply. As an attempt to reduce the first barrier Daylight 1-2-3 was to report a variety of climate-based metrics e.g. daylight autonomy (Reinhart and Walkenhorst 2001), useful daylight illuminance (Nabil and Mardaljevic 2005) and daylight saturation percentage (CHPS 2006). The development team further hoped that reporting the different metrics side-by-side could help to advance the ongoing debate about the merits and pitfalls of the individual metrics.

Table 1 presents the resulting list of requirements that guided the Daylight 1-2-3 project team during the development of the tool.

Table 1. List of requirements for Daylight 1-2-3.

<b>Requirements for Daylight 1-2-3</b>
Space types covered: open-plan offices, classrooms/ conference rooms, private offices
Simulation inputs: simple, large variety of building sites, varying façade orientations, façade layouts and components, sidelighting as well as toplighting
Simulation outputs: climate-based daylighting metrics and monthly total energy loads
GUI: intuitive navigation, visual, easy-to-use, allow

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the user to store simulation results locally

Simulation engine: stable, validated, fast, integrated thermal/ lighting computation capabilities

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## TECHNICAL SOLUTIONS

Once the requirements for Daylight 1-2-3 had been established, the project team developed the technical solutions to meet them. A particular challenge was to provide a fast yet reliable integrated lighting/thermal simulation engine.

### The Daylighting Engine

The first step was to identify a suitable daylighting engine. While radiosity-based tools offer increasingly reliable results, the Radiance raytracer remains the only daylight simulation engine that has been validated for full scale geometries featuring light shelves (Mardaljevic 2000), venetian blinds (Reinhart and Walkenhorst 2001), and translucent panels (Reinhart and Andersen 2006). These validation studies have further shown that Radiance can be combined with a daylight coefficient approach to reliably model the changing levels of daylight in a building over the course of a year. Radiance further offers the flexibility to model more complex fenestration systems such as laser cut panels (Greenup et al. 2000). These advantages pointed towards using a Radiance-based daylight coefficient approach for Daylight 1-2-3.

### Client-Server Application

A drawback of using Radiance remained that – depending on the scene’s complexity – simulations would have taken several hours while the target simulation time for Daylight 1-2-3 was in the order of a minute. Earlier experiences with the Lightswitch Wizard had shown that using a database of pre-calculated daylight coefficients significantly reduces the time for an annual simulation (Reinhart et al. 2003). Since such a database requires a substantial amount of disk space (several gigabytes), the Daylight 1-2-3 development team opted for a similar approach as for Lightswitch Wizard, i.e. to split the graphical user interface (GUI) and the simulation engine into two stand-alone applications. As shown in Figure 1,

the GUI resides locally on the user's PC and allowing him or her to set up a simulation, run it via the internet on a central server, and store and analyze the results locally. The simulation engine resides on the server and consists of a customized version of ESP-r as well a two daylighting databases (Figure 2).

**Integrated Thermal-Lighting Simulations**

ESP-r was chosen as the thermal engine since it is well established (ESRU 2007) and features an open architecture that offers peer-validated computation modules and flexibility in capacity enhancements. Members of the development team had acquired previous experience with ESP-r as they had successfully developed another ESP-r based online application (Purdy et al. 2005). Another argument for using ESP-r was that it had already been coupled with a Radiance-based daylight coefficient approach (Janak 1997). Building on this initial work, several modifications were implemented to improve the ability of ESP-r to model daylight spaces, to speed up the time required for an annual simulation, and to offer a wider variety of façade variants.

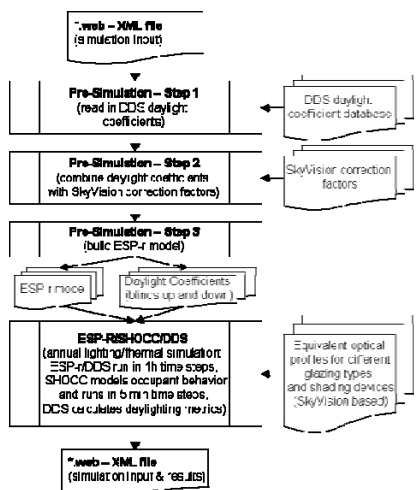


Figure 2 Flow Diagram of the daylight 1-2-3 simulation engine.

**Dynamic Daylight Simulations (DDS)**

DDS is a new daylight coefficient model for dynamic daylighting simulations (Bourgeois et al. 2007). The model was developed as a mechanism for sharing daylight coefficient data between lighting and energy simulation programs. Its main advantage within the context of Daylight1-2-3 is that the DDS file format is independent of building orientation and location. This allows Daylight 1-2-3 to offer an analysis of daylight spaces with arbitrary façade orientations located at hundreds of locations worldwide. A new module was added to ESP-r allowing it to read in and process DDS-type daylight coefficients for a fully integrated lighting/thermal simulation (Bourgeois et al. 2007).

The DDS module currently reports daylight factor, daylight autonomy, continuous daylight autonomy, useful daylight illuminance, daylight saturation percentage, and annual light exposure.

The use of the DDS file format reduces the size required by the daylight coefficient database but the need to offer a large set of façade geometries, room dimensions, and material surfaces would still have required a gigantic database. Daylight 1-2-3 therefore uses a 'trick' to cover a large number of façade layouts. As shown in Figure 3, the exterior façade is divided into several façade fields (nine in the case of a private office).

1	2	3
4	5	6
7	8	9

Figure 3 Façade section for a private office. The material properties of nine façade fields can be set independently.

For each façade field a set of daylight coefficients has been calculated and entered into a database. For each of these sets one façade field has a clear double glazing whereas all other façade fields remain opaque. A variety of room dimensions and material properties are covered. During a Daylight 1-2-3 simulation the user can set the material properties for all nine fields independently and – since daylighting is largely additive – the daylight distributions for several glazed façade fields can simply be calculated by adding up the daylight coefficients from the database for the individual façade fields. Using the façade fields leads to 512 different façade geometries for open-plan and private offices and 2048 combinations for classrooms.

**Skyvision Correction Factors**

Apart from the basic choice of whether a façade field is opaque or not, the user can further specify a single, double, or triple glazing. In addition, several common glazing coatings such as 'bronze' or 'low-e cold climate' can be specified and combined with internal or inter-pane venetian blinds. In order to also explore the benefit of skylights, up to four skylights with varying material properties can be added. These additional options result in hundreds of thousands of different daylighting designs for each space type. As an example, Figure 4 shows a classroom facing Southwest with a band of clear, low-e, double glazed clerestories, two view windows with internal venetian blinds, and four double white acrylic skylights.

This wide selection of material properties for each façade field is realized by combining the daylight coefficients from the database with 'SkyVision

correction factors' (Laouadi *et al.* 2007). The process works as follows: All daylight coefficient sets in the database are based on Radiance calculations using a reference glazing with a visual transmittance of 80%. While it would have been technically possible to generate multiple copies of these daylight coefficient sets for all different glazing types and shading device settings, populating the resulting enormous database would have taken a long time. In order to be more flexible, the SkyVision software was therefore modified to provide visual transmittance values of the supported glazing types and Venetian blinds according to the DDS daylight coefficient format (Laouadi *et al.* 2007). The visual transmittances are multiplied with the daylight coefficient sets from the database resulting in two new sets of daylight coefficients: One set for the venetian blinds opened and one set for the venetian blinds closed. SkyVision correction factors treat the venetian blinds as a continuum with mean light transmitting and redirecting properties. The method has been successfully compared to explicit Radiance simulations (Laouadi *et al.* 2007).

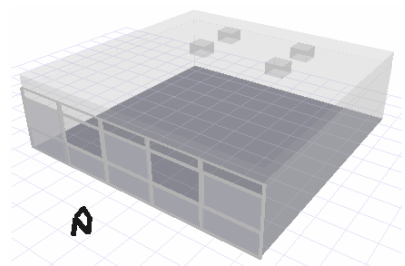


Figure 4 Daylight 1-2-3 model for a side and toplit classroom.

### Preparing an ESP-r Model

As shown in Figure 2, two model-specific sets of daylight coefficients (Venetian blinds all up and down) are generated during the first two pre-simulation steps. During the third pre-simulation step a 'simulation wizard' is invoked that has been specifically developed to facilitate the efficient development of web applications using ESP-r. The simulation wizard starts with a reference model and builds a complete, customized ESP-r model through a series of replacement tags and automated geometry manipulation (scaling, adding surfaces etc.).

During the main ESP-r/SHOCC/DDS simulation step (Figure 2) the two daylight coefficient sets are read in via the DDS module for a fully integrated lighting/thermal simulation. Skylights and windows with shading devices are thermally modeled as one glazing layer with equivalent optical and thermal characteristics. The equivalent optical profiles required by ESP-r to characterize the glazing layer (solar transmittances, effective physical properties

for conductivity, etc.) were previously generated by SkyVision for the supported glazing and shading types.

### Modeling Occupant Behavior

Once the amount of daylight within a space has been established, the status of the venetian blinds and the electric lighting over the course of the year depends on the type of controls provided to the occupants (on/off switch, occupancy sensor, dimmed lighting) as well as how the occupants use these controls. Previous research on occupant use of personal controls resulted in an occupant behavior model (Reinhart 20004) that was implemented into ESP-r via the SHOCC module (Bourgeois *et al.* 2006). The model predicts when users will lower window blinds in response to glare, or when they will switch on the electric lighting. The model features an active and a passive behavior mode and the Daylight 1-2-3 GUI allows the user to specify a mixing ratio of active versus passive occupants.

The Lightswitch algorithm requires SHOCC to run in five-minute time steps. In order to reduce the required simulation time the ESP-r - SHOCC interaction was reconfigured to allowing the 'parent application' (ESP-r) to advance in one hour time steps while SHOCC still runs in five minute time steps (Bourgeois and Reinhart 2007).

### Reporting

ESP-r was also modified to allow it to output XML using an XSLT processor. During a simulation an XML input string is transmitted over the internet to the calculation server. Once completed, simulation results (in XML format) are transmitted back to the user's PC for presentation and storage (Figure 2).

### DAYLIGHT 1-2-3 VERSION 1.0

Daylight 1-2-3 can be downloaded free-of-charge from [www.daylight1-2-3.com](http://www.daylight1-2-3.com). The JAVA GUI consists of an input section on the left and a 3D model viewer on the right (Figure 5). The model viewpoint can be interactively changed using the mouse. In order to set up a simulation the user has to go through a series of submenus in the input section and model a space that reflects the prospective design as closely as possible. Before running a simulation all input data is saved in a project file on the user's hard drive. The user's PC only needs to be connected to the internet during a simulation which takes between 30 and 90 seconds depending on the size of the model and server traffic. This low simulation time is the result of the various optimization routines of the simulation engine described above.

Once a simulation is complete, simulation results are added to the project file and displayed for further analysis in the 3D model viewer. The user's PC does not need to be connected to the internet to analyze the data. Several data representation modes are available to visualize the results. The daylighting mode (Figure 6) allows the user to view daylight factor and several climate-based metrics as falsecolor maps. The energy mode (Figure 7) presents monthly energy loads for heating, lighting, and cooling.

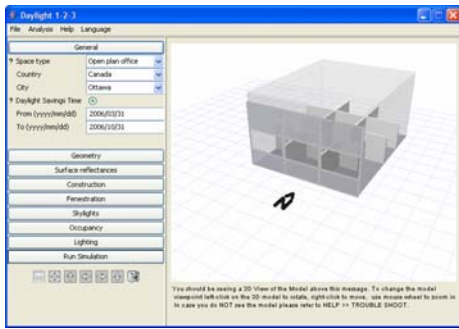


Figure 5 Entrance view of the Daylight 1-2-3 GUI version 1.0.

## CASE STUDY

This section provides a fictional example of how Daylight 1-2-3 could be used during the design of a series of identical classrooms in a primary school in Ottawa, Canada. Interior classroom dimensions are 10m x 10m x 2.5m. The façade design of the classrooms corresponds to that in Figure 4. The classrooms are typically occupied by 20 students plus teacher, are only used during the school year, and face southwest. The target illuminance level throughout the classroom is 400 lux.

The design team wants to know what the daylighting and energy implications of adding skylights and/or a photocell controlled dimming system. Daylight 1-2-3 is used to address these two questions.

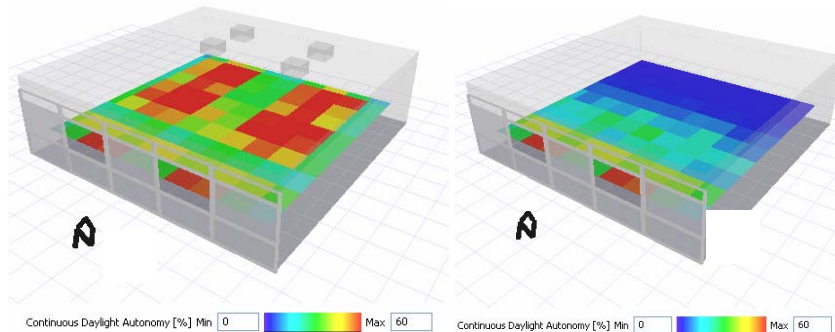


Figure 6 Continuous daylight autonomy distribution in the classroom from Figure 4 with (left) and without (right) skylights. The classroom is located in Ottawa, Canada, and has a target illuminance of 400lux.

Figure 6 shows the continuous daylight autonomy distribution of the classroom with and without skylights. Continuous daylight autonomy ( $Da_{con}$ ) is a measure of the annual amount of daylight in a space during occupied hours. If during an occupied hour the horizontal illuminance at work plane height lies above the target level of the space, the daylighting criteria is fully met at this point. Partial credit is given if daylighting levels lie below the target level, e.g. a partial credit of 25% is given if the illuminance lies at 100lux and the target level is 400 lux ( $100\text{lux}/400\text{lux}=25\%$ ). Figure 6 shows that for the classroom with skylights  $Da_{con}$  lies between 35% and 60% throughout most of the classroom. Without skylights these levels drop below 30% at more than 3m away from the facade. Figure 6 clearly shows the positive impact of the skylights on the uniformity and quantity of daylight within the space.

Figure 7 shows monthly energy loads for a classroom with skylights for a 'typical' lighting system with just an on/off wall switch.

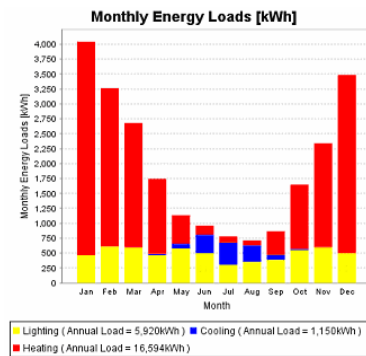


Figure 7 Monthly energy loads for the classroom from Figure 4 with skylights and a manually controlled electric lighting system.

As one would expect for Ottawa the energy loads for heating dominate. There is some minor demand for mechanical cooling in the summer which would typically not be met since primary school

classrooms in Ottawa are not used from early June to early September.

Figure 8 shows the primary energy use in the classrooms with and without skylights and photo-cell controlled dimming, assuming no mechanical cooling. To get from energy loads to primary energy use the following assumptions were made: A three-to-one primary-to-secondary electricity conversion factor from fossil fuels and a global transportation and distribution loss of 90% for fossil fuel for heating. At the building level, heating is provided with an efficiency of 85%, and lighting efficiency is assumed to be 100% (Bourgeois et al. 2006).

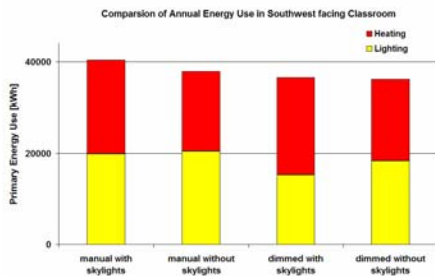


Figure 8 Primary energy use for the classroom from Figure 4 located in Ottawa, Canada, with and without skylights and with and without photo-cell controlled dimming.

Figure 8 shows that adding only skylights (even though it improves the daylighting in the classroom) comes with an overall energy penalty of 7% compared to the reference case (manual without skylights). The reason for this additional energy use comes from increased thermal losses during the heating season due to the skylights ( $U\text{-value}_{\text{skylight}} = 2.57 \text{ W/m}^2\text{K}$  as opposed to  $U\text{-value}_{\text{roof}} = 0.29 \text{ W/m}^2\text{K}$ ). Introducing dimming reduces the reference value by 5% whereas introducing skylights and dimming leads to a 4% overall energy reduction. In the latter case the significant lighting savings from the dimming system due to the skylights are counterbalanced by the poor thermal performance of the skylights. This simple analysis shows that for this particular climate, building type and material selection skylights - as far as energy is concerned - only make sense if combined with photocell-controlled dimming. Adding skylights to a classroom with dimming controls does not improve the space's overall energy balance. In other words, the premium paid for installing skylights cannot be justified through energy savings. On the other hand, Figure 6 clearly shows a significant gain in the uniformity and visual appearance of the space due to the extra daylight. It would remain up to the design team to decide whether these benefits for the users merited the installation of the skylights or not.

## DISCUSSION AND CONCLUSION

The previous section revealed that different daylighting technologies can at the same time have positive and negative effects on a space as far as daylighting and energy are concerned. This finding shows that Daylight 1-2-3 can play an important role in helping design teams make more informed design decisions. Daylighting measures tend to be portrayed as being universally positive, suggesting that more, controlled daylight *always* improves the daylight quality of a space and saves energy at the same time. The foregoing analysis revealed that reality is not that clear cut: In cold climates skylights with mediocre thermal properties can outweigh their own lighting energy benefits by introducing extra heating needs. In contrast, Figure 9 shows similar results to those from Figure 8 with the classrooms located in Los Angeles, USA. In this climate – even without active cooling – overall energy savings from skylights combined with dimming amount to an impressive 25% compared to the no dimming/no skylights reference case.

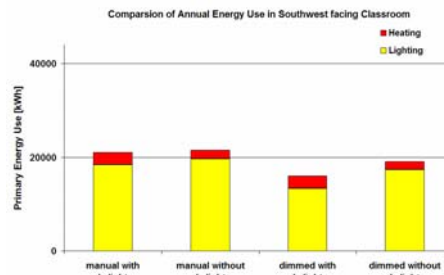


Figure 9 Primary energy use for the classroom from Figure 4 located in Los Angeles, USA, with and without skylights and with and without photo-cell controlled dimming.

The case study further demonstrated that Daylight 1-2-3 can be used to quickly evaluate the energy and daylighting implications of key design measures. Considering that generating the numbers for Figures 6 to 8 took less than an hour, the tool can be applied at the initial design stage when key decisions regarding the use of energy saving components are generally made (de Wilde et al. 1999). The tool also lends itself to be used for educational purposes. A practical problem that an educator would currently face when using Daylight 1-2-3 during a classroom session is that the simulation time would substantially increase if a dozen students synchronously repeated a demo on their laptops. The authors hope to soon enhance the capacity of the Daylight 1-2-3 server by adding extra CPU nodes.

Another limitation of the tool remains that the effect of neighboring buildings is not considered. This limitation is currently being addressed.

A remaining, significant challenge is to help the design community to develop an understanding of the value and opportunities offered by the new metrics proposed and to enhance design practices that still largely rely on rules-of-thumb and experience from previous work.

Summing up, Daylight 1-2-3 is a new, easy-to-use daylighting/energy design support tool specifically geared towards simulation novices. While simulation times are in the order of one minute the quality of the simulations can be considered state-of-the-art, being based on Radiance, ESP-r, and the latest generation of occupant behavior models. The tool outputs a variety of climate-based daylight performance metrics. This widens the number of practitioners that can apply these new metrics in their projects.

### ACKNOWLEDGMENT

The development of Daylight 1-2-3 was supported by the Panel for Energy Research and Development (contract number PERD082), BC Hydro, the National Research Council of Canada as well as Natural Resources Canada. The authors would like to thank Steve Ouellet (NRC computer support) and Peter Richards (NRC graphic design) for their valuable contributions to the project.

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