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DEFINITION OF A REFERENCE OFFICE FOR STANDARDIZED EVALUATIONS OF DYNAMIC FAÇADE AND LIGHTING TECHNOLOGIES

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ABSTRACT

This paper proposes a modeling and analysis convention for a side- and/or toplit space called the 'reference office'. The reference office is meant to act as a baseline for comparative analyses of different façade and/or electric lighting technologies and may be used in research (facilitating the comparison of results from multiple studies) in practice (for product rating) as well as in architectural education (enabling students to contrast their design ideas to a set of standard design solutions). The reference office represents a somewhat typical 'shoebox' model as is commonly used for conceptual design explorations. Interior walls are adiabatic allowing the user to concentrate on the thermal impact of various façade technologies. The shoebox is comparatively 'deep', more than three times the window head height, so that the impact of light redirecting façade technologies and shading control strategies can be resolved. Venetian blinds are manually controlled to avoid discomfort glare throughout the office. As a proof of concept a window-to-wall ratio (WWR) study of daylight availability, occupant comfort and operational energy use in the reference model is presented using Radiance/DAYSIM simulations in combination with EnergyPlus. The study suggests that for Boston a preferred South facing WWR is 40%.

INTRODUCTION

In recent years significant progress has been made towards the development of computational methods that holistically evaluate the performance of daylit spaces regarding annual daylight availability, occupant comfort and energy efficiency (Reinhart & Wienold 2011). Simulation results can now be presented in 'dashboard' type overview sheets that present the performance of a space for multiple design performance criteria. In tandem with those efforts, software developers have prepared workflows that largely automate the generation of such dashboard results (Solemma 2012, LBNL 2012). While the effort level required to master those workflows is decreasing, there is still a significant degree of training required for architects and/or consulting engineers to effectively use these tools. As additional training translates into resources that many building projects cannot afford, further effort has gone into the development of 'easy to use' environmental performance tools with notable examples being MIT Design Advisor (Brown, Glicksman and Lehar 2010), ComFen (LBNL 2012) and (now discontinued) Daylight 1-2-3 (Reinhart, Bourgeois, Dubrous, Laouadi, Lopez, Stelescu). These tools allow the modeling of rectangular sidelit and/or toplit spaces with adiabatic interior walls so that the thermal effect of different building envelope variants can be resolved. Throughout this manuscript, this type of space is called a 'shoebox' model. An advantage of shoebox models is that the results are simple to read and interpret and that the effect of key design parameters such as glazing type and window size can be analyzed quickly. An impediment of shoebox-based tools is that many users, particularly designers working on a whole building, tire quickly of 'the box' and desire more geometric variety. An alternative to geometrically limited tools is therefore to include a shoebox template in more flexible environmental performance design tools*,* allowing users – as part of an initial training – to apply a tool to an easy to interpret space before venturing out into more complex geometries.

Following this train of thought, shoebox models constitute a meaningful point of departure in any type of simulation tool. Given their significance, this paper proposes a set of simulation assumptions, dimensions and usage patterns as well as an analysis framework for a standard shoebox model. The authors henceforth refer to these specifications as the 'reference office'. The reference office corresponds to a standard top- and/or sidelit shoebox model as earlier described. Care has been taken to define a space that can be used to resolve the overall daylighting, occupant comfort and thermal performance for a wide range of facade designs and environmental control strategies.

The reader might wonder what could possibly be the benefit of such an overly prescriptive set of specifications? Why should exact dimensions or schedules matter that much given that those assumptions are never met in any real space anyhow (ASHRAE 189.1)? Why propose a standard set of simulation outputs? The authors identified the following arguments for introducing a standard shoebox model for research, architectural education and product rating.

Research Effectiveness

Shoebox models have long been the default model type within the building performance simulation community to showcase new modeling techniques or the impact of key design parameters such as façade design and electric lighting controls: A non-exhaustive review of IBPSA's *Building Simulation* conference proceedings since 1997 yielded over forty papers using shoebox type models, referring to them as a 'typical', 'standard', 'test', 'sample' or 'reference' office. Interior dimensions of these spaces mostly vary between 3 and 5 meter width, 5 to 8 meter depth and 3 to 4 meter height. Occupancy schedules generally vary from weekdays 8AM to 8PM down to 9AM to 5PM. As one might expect, at least one of the locations of the test spaces usually corresponds to that of the respective authors' home institution. Thermal and optical properties of envelope components tend to be equally based on construction practices in the corresponding authors' jurisdiction.

While the variety of shoebox models introduces a regional flavor to building performance simulation studies, it undermines any attempt to directly compare results between different studies. Say if a photocell controlled dimming systems saves 30% of electric lighting energy in one study and adding a light shelf reduces electric lighting and cooling loads by 25% in a second study. How is one to judge which technology is more effective if the first study was based in Freiburg, Germany, and assumed 25% longer occupancy than the second study set in Boston? One might rightfully argue here that the effectiveness of many technologies is climate-dependent which is why building performance simulation tools are necessary to begin with. But, the authors argue that there is merit in working with the same set of assumptions and to always include a few core representational climates. Otherwise, each simulation study will continue 'reinventing the wheel', showcasing new modeling capabilities but providing limited overall relevance of the actual technologies modeled.

Product Comparisons

The desire to compare results from different studies becomes even more relevant as one ventures into product selection. Any manufacturer's claim that 'a certain glazing technology saves 80% compared to conventional glazings' should be eyed with suspicion. 'What was that 'conventional glazing'? What window-to-wall ratio was assumed, facing which way? It seems to be in the interest of the consumer that manufacturers' claims are substantiated along the following lines: 'Compared to the reference office this technology saves 20% in annual cooling loads in Phoenix.' This seems to be especially important since apart from how to simulate a space there is currently also limited rapport within the architecture, engineering and construction community as to what performance metrics to use. If manufacturer A reports energy savings compared to a reference spaces without blinds and with the lights constantly switched on during occupancy whereas manufacturer B compares a product to a space with manually controlled electric lighting and blinds, the products are impossible to compare.

The critical reader might again pause at this point and ponder that an overprescribed reference case might inadvertently bias product comparisons if a particular product works best under a specific set of conditions, say for facades that mainly experience low sun angles. For such cases the authors recommend that a manufacturer adopts the reference office by – for example – rotating it towards the West. A resulting statement could be that a certain product 'saves 30% in annual heating load for a West facing façade'. Apart from improved transparency, a benefit from such a statement is that consumers would be directed towards appropriate applications of a technology.

Architectural Education

A benefit of using a standard reference office in architectural education is that students can be taught the effect of various technologies applied to the same reference case. In fact, the first author already uses the reference office throughout a semester-long daylighting class for this purpose, introducing different daylighting concepts from glazing type to locations, façade orientation and window design (Reinhart 2013). Students thus become increasingly familiar with the daylight performance characteristics of the space, which in turn helps them to judge the relevance of different measures before they apply them to their own designs. A secondary benefit of having access to a reliable simulation model is that simulation novices can use the model to initially familiarize themselves with a meaningful set of simulations assumptions.

REFERENCE OFFICE DESCRIPTION

The reference office is meant to represent a South facing sidelit office located in Boston, MA, USA, as its base climate. The office is not obstructed by neighboring buildings. Its interior room dimensions are 3.6 m x 8.2 m x 2.8 m (Figure 1). The large room depth of 8.2 m, which corresponds to nearly 3.5 times the floor to ceiling height, was consciously chosen to be rather large so that the effect of daylighting remains visible for all variants. The reader may think of the office as one of multiple identical spaces in a building (Figure 2). The window-to-wall ratio (WWR) of the rough opening compared to the interior dimensions is 45%. Assuming an interior wall thickness of 0.15m and a floor to floor distance of 3.1m the exterior WWR of

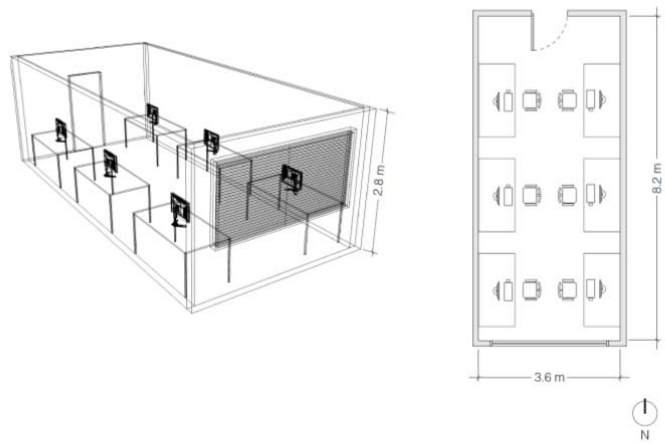

Figure 1: *Perspective view and floor plan of the reference office*

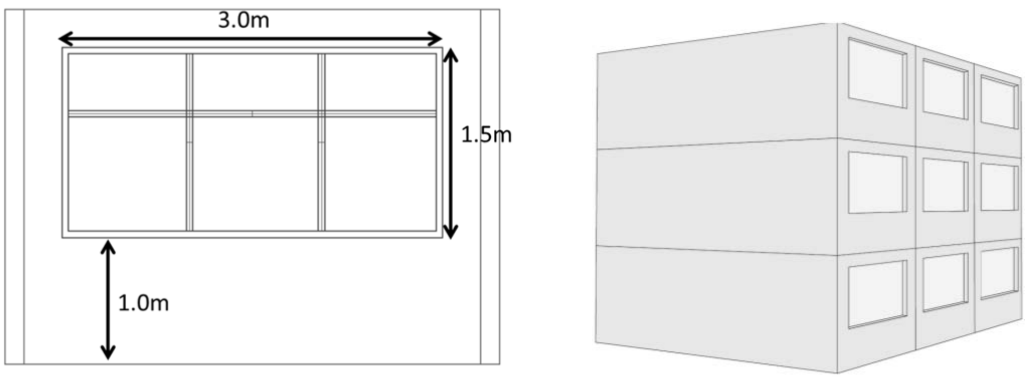

Figure 2: *Façade section and view of multiple reference offices stacked together to form a facade*

the facade in Figure 2 is 39%. The outer frame and mullion width is 0.05m leading to a frame factor of 16% of the rough opening area of the window.

Usage Pattern

The office is occupied daily from 8AM to 6PM with daylight savings time lasting from the second Sunday in March to the first Sunday in November. This admittedly unrealistically high occupancy rate was selected to gage the *potential* impact that various energy efficiency measures can have on the space. The occupancy schedule is in agreement with the IESNA's new Lighting Measurement IES LM-83-12 which promotes climate based daylighting metrics (IESNA 2012). During hours of occupation it is assumed that four out of the six workspaces shown in Figure 1 are occupied and that occupants are performing regular office work including working on a computer. The resulting peak occupant load is 7.38m^2/occupant. The choice of reducing occupancy and activity to two thirds of seating capacity is that the resulting internal loads are more realistic and allow the design of the façade to have a noticeable impact. Instead of just modeling four work spaces to begin with six workstations were modeled to show the impact of allowing occupants to move around the space. During hours of occupation heating and cooling set points are 20^{o}C and 26^{o}C, respectively. Setback temperatures are 15^{o}C and 30^{o}C. The office is equipped with an external, manually controlled venetian blind system. The target work plane illuminance is 300 lux. The electric lighting is manually controlled according to the Lightswitch model (Reinhart 2004) using a bi-level wall switch that independently controls the lighting for occupants sitting in the first two rows and separately in the back row. The installed lighting power for each row is 100W corresponding to four TL5 recessed downlights per row. The resulting lighting power density for the office of 10.1 W/m^2. The motivation for splitting the office into two lighting zones is to be able to show in how far various design interventions at the façade level change annual daylight availability as well as electric lighting use. If instead the electric lighting was wired as a single control zone in a space as deep as the reference office, the lighting would be mostly switched on during all occupied hours independent of the façade design since it is difficult to consistently get daylight to the third row. Peak plug loads in the office are 8W/m^2 corresponding to one *Energy Star* rated LCD monitor and laptop per occupant present.

Building Components and HAVC

Optical and thermal properties of all building components are listed in Table 1. The thermal

Table 1 *Optical and thermal material properties*

Glazing	Double glazing without low-e coating: τ_{vis} = 65%; SHGC= 28% ; U-Value= 1.6W/m^{2}K
Interior Walls	Lambertian diffuser with a 50% reflectance; adiabatic surface
Exterior Wall	Lambertian diffuser with a 50%/35% (inside/outside) reflectance; U-value= 0.365 W/m^{2}K
Ceiling	Lambertian diffuser with an 80% reflectance; adiabatic surface (office not under a roof)
Floor	Lambertian diffuser with a 20% reflectance; adiabatic surface
External Ground	Lambertian diffuser with an 20% reflectance
Shading	Semi specular exterior blinds with a diffuse reflectance of 50% and a specular component of 15%.

properties were assigned according to ASHRAE 90.1-2007 Table 5.5-5 (Addenda G) for Boston which is located in ASHARE 169-2006 climate zone 5A. The infiltration rate is 0.5 ac/h. As already stated, the main purpose of the reference model is to explore various façade an electric lighting design options. On the other hand, conducting a detailed HVAC analysis of a shoebox model is – in the authors' opinion – of limited use. Nevertheless, for the purpose of translating space loads into energy use, operational energy costs and carbon emissions, it is assumed that the reference office forms part of a medium sized multistory office building (~2300m^2). According to ASHRAE 90.1-2007 (Table G3.1.1), the baseline HVAC system for such a building is a packaged rooftop VAV unit with reheat (ASHRAE. 2007). Cooling and heating energy consumption calculations are simplified by multiplying loads by a annual mean COP of 3.02 for the cooling system and 0.8 for a natural gas boiler as per ASHRAE/USGBC/ANSI 189.1 (2010) for >70kW and <223kW cooling capacity. No plenum is considered. Ventilation rates are assumed as per ASHRAE guidelines. Only energy use for conditioning the fresh air is considered.

Simulation Setup

Since the shading device and electric lighting are manually controlled it is worthwhile discussing how the simulation should be set up. The authors are using a combination of the Radiance-based DAYSIM program (Ward and Shakespeare 1998; Reinhart and Walkenhorst 2001) with EnergyPlus (US-DOE 2013). DAYSIM calculates annual illuminances profiles across the reference office. Using the *gen_dgp_profile* program in DAYSIM, written by Jan Wienold, daylight glare probability (DGP) levels for six view point located at the six workstations facing the monitors are calculated for each hour of the year (Figure 3) (Wienold 2006). When the DGP value at any of the six work stations is 'disturbing' (larger than 0.4) during occupancy, blinds are lowered. Blinds are retracted during arrival in the morning or after lunch. Similarly, the bi-level lighting system is controlled through six 'work plane sensors' associated to the two lighting systems as required by DAYSIM's Lightswitch model for an active user (Reinhart 2004). The resulting occupancy, shading and lighting schedules from DAYSIM are then fed into a two zone layered construction EnergyPlus 7.0 model of the space (Figure 4). DIVA-for-Rhino Version 2.0 was used as the simulation interface for this study (Solemma 2012, Jakubiec 2012). Suggested Radiance simulation parameters are listed in Table 2. These values are calibrated such that the effect of complex fenestration devices will be accurately represented throughout the depth of the reference office.

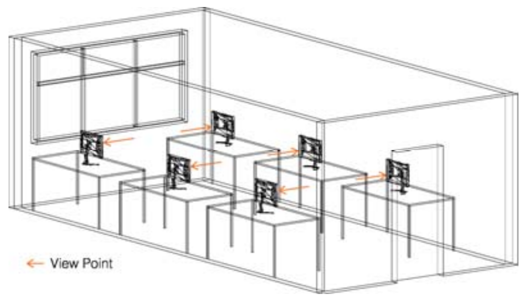

Figure 3 *View points in the reference office*

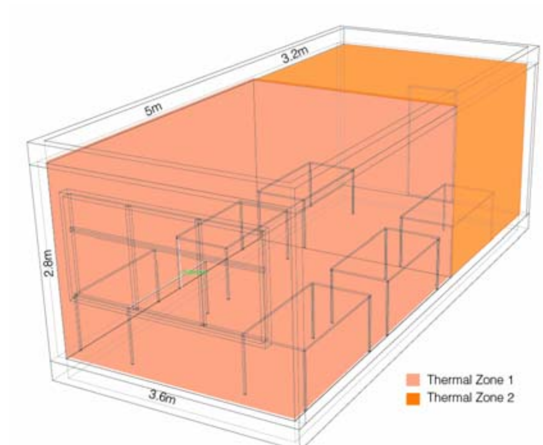

Figure 4 *Two zone thermal model*

Table 2 *Radiance simulation parameters*

ambient bounce	7
ambient division	1500
ambient sampling	20
ambient resolution	300
ambient accuracy	0.05

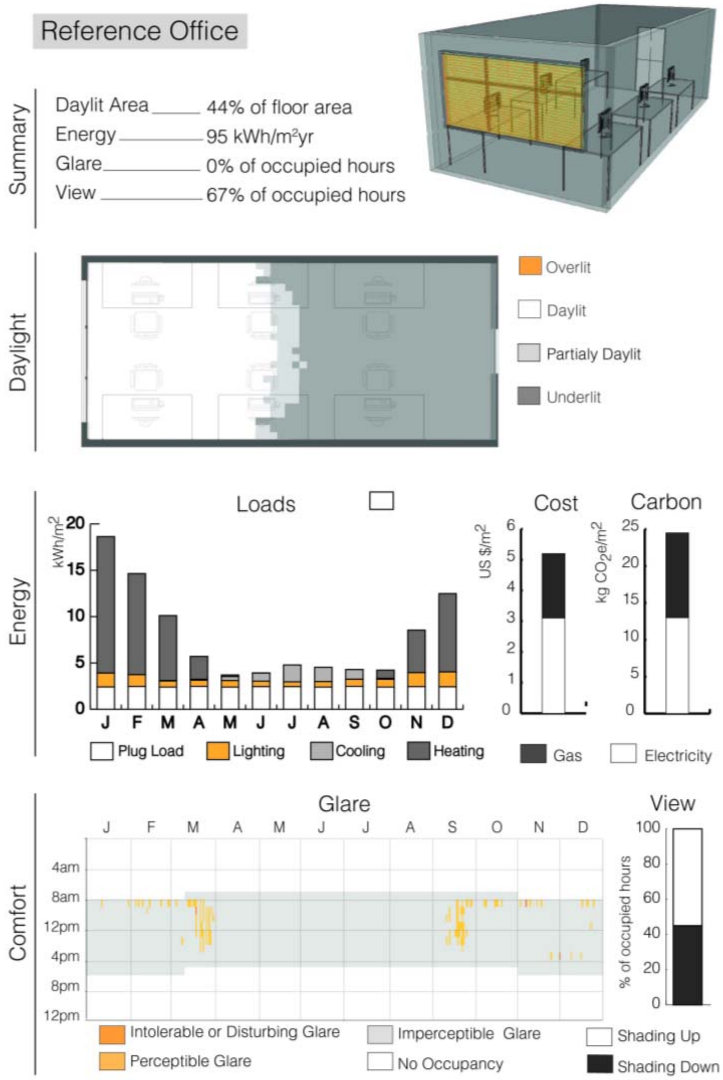

Figure 5: *Dashboard view of the reference office*

ANALYSIS FRAMEWORK

Single Design Variant

Once an integrated thermal and lighting simulation has been conducted, the results have to be presented in a meaningful fashion. While performance metrics of operational energy use are well established with examples being monthly loads, annual costs and carbon emissions, ways of how to describe the daylight within a space are still evolving. As described in detail in previous work, the authors promote modeling daylighting and energy use in a fully integrated, consistent way that includes occupant behavior and/or automated controls and to present results separately for daylight availability, occupant comfort and energy use (Reinhart and Wienold 2010). For daylight availability this study uses a daylight autonomy level with a target illuminance of 300lux above 50% to denote the boundary of the daylit area (IESNA 2012). Placeholders for occupant comfort are the occupied time in the year at which any work place has a daylight glare probability above 40% (disturbing glare) and how often the blinds are opened giving occupants a view outside. An example 'dashboard view' is shown in Figure 5.

The figure shows that 44% of the space is daylit and that the daylit area expands until about the middle of the second row of workspaces. This confirms that indeed this is the area where improved daylighting design may have an impact on both occupant comfort and energy use. While energy use is predominated by heating, the majority of costs and carbon emissions stem from electricity use. The assumed energy costs are 0.179 $/kWh and 0.043 $/kWh for electricity and gas, respectively (US-EIA 2013). Corresponding carbon emissions are 0.758 kg CO_2e/kWh for electricity and 0.232 kg CO_2e/kWh for gas (ASHRAE 189.1). The external venetian blinds effectively mitigate glare throughout the year with

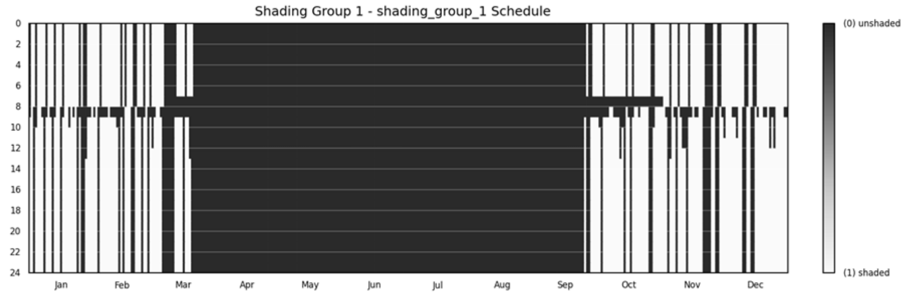

Figure 6 *Status of the shading system throughout the year for the reference office (DIVA 2.0 output)*

some perceptible glare occurring during the transition periods in March and September. Figure 6 shows the status of the shading device throughout the year, revealing that – due to lower solar angles – the blinds are frequently closed during the winter and remain opened during the summer as the sun cannot penetrate into the space. This is the case because the space is air conditioned and the occupants will not experience any overheating during the summer months. The results would differ if the space was naturally ventilated.

Parametric Studies

Examining one design variant in detail is instructive but – if one wants to use simulations to 'drive' design decisions – being able to assess multiple variants at a time becomes crucial. A popular (and relevant) analysis conducted with shoebox models is to determine the behavior of a space for varying window-to-wall ratios. Since the actual position and shape of the window do not matter from a thermal simulation standpoint (if one ignores effects of daylight on electric lighting use) previous studies tended to place the window in the center of the façade enlarging it linearly (Ochoa Morales, Aries, van Koenen and Hensen 2012). To lend more 'architectural realism' to these assumptions, the reference office comes with a set of recommended window opening patterns with varying window sizes (Figure 7). Wherever possible, window dimensions in multiples of 0.5m were chosen. In agreement with ASHRAE convention, WWRs are expressed with respect to the outside gross façade area.

Figure 8 shows an effective way to present the performance dynamics in the reference office for the different WWR variants from Figure 7. The top plot in Figure 8 contrasts the size of the daylit area versus the percentage of the time when the blinds are opened and the occupants have a view to the outside. It turns out that the external venetian blinds effectively prevent glare from occurring so that none of the variants is encountering glare for more than 0.8% of the occupied time in the year for any work space. In absence of a window (WWR=0%) there is trivially no view or daylight. The daylit area then rapidly grows for increasing WWRs and saturates at about 45% of the area of the office for WWRs of 39% and beyond. Interestingly, a view to the outside is most frequently maintained the smaller windows (over 90% of the time for a WWR of 20%) but these numbers keeps falling as the window area increases. The reason for this is that larger windows are more

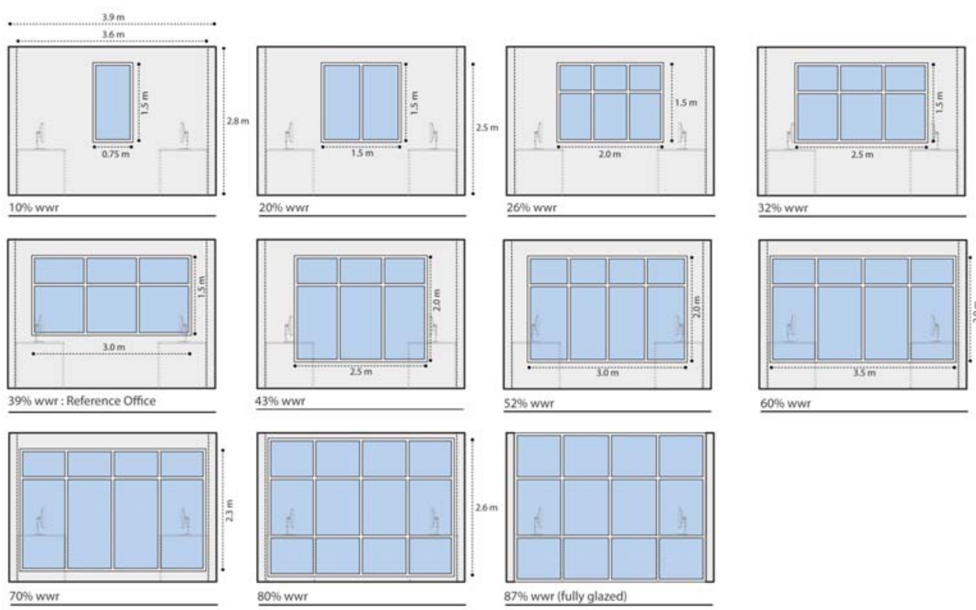

Figure 7 *Window-to-wall ratio layouts for the reference office*

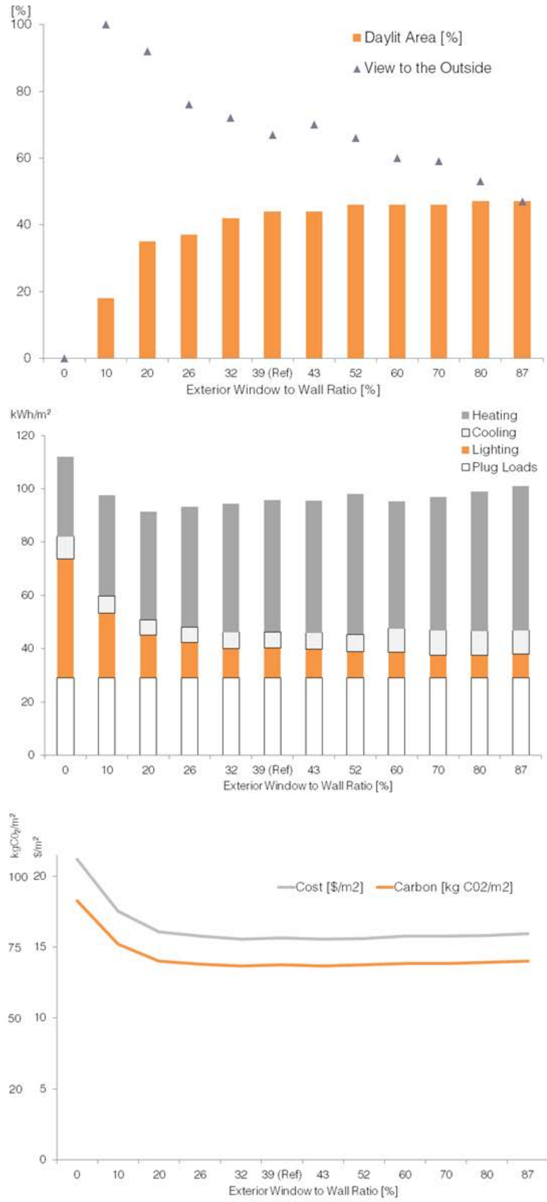

***Figure 8** Window to Wall Ratio Study for the reference office*

likely to trigger discomfort glare which in turn causes occupants to lower the blinds. From a combined daylit area and view standpoint, the optimum size of the window for the reference office is hence in the order of 40%.

The middle and lower plots in Figure 8 show heating, cooling, lighting and plug loads as well as overall costs and carbon emissions. The sum of all loads rapidly falls for smaller windows along with the electric lighting use and then start rising again beyond a WWR of only 20%, mainly due to increased heating loads. For carbon emissions and costs the numbers also fall initially for low WWRs but practically plateau for WWRs above 32%. Between a WWR of 32% and the fully glazed variant annual operating nominally costs rise from 15.6 $\$/m^2$ to 16.0 $\$/m^2$. This difference is smaller than the expected accuracy of the simulation. Figure 8 hence suggests that the preferred WWR for the reference office facing South in Boston lies around 40%, which happens to coincide with the base case. Smaller windows lead to a reduced daylit area and (below 20%) severe penalties for costs and carbon emissions. For larger windows energy penalties are moderate but more glazing has also no direct benefit for daylighting as the effectively daylit area remains the same. In fact, blinds tend to be closed more often to mitigate glare which suggests a net loss in visual comfort.

DISCUSSION

The foregoing section showed that the reference office can be used to extract valuable design information for sidelit spaces. It is interesting to discuss the WWR study presented in Figure 8 in the context of ASHRAE Standard 90.1 which requires WWRs in Boston to remain between 0% and 40%. According to Figure 8 WWRs should at least be 40% for a South facing office space in Boston for daylighting to reach its full potential. In fact, increasing window area even to very high levels seems to have limited environmental consequences since a good double glazing plus coating in combination with dynamic shading offers effective protection against the outside.

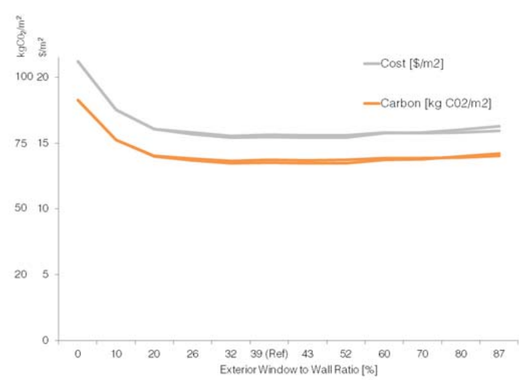

***Figure 9** Costs and carbon emissions for the reference office with interior blinds*

The reader may wonder whether the fact that the reference office has external venetian blinds, which remain rare in the United States at least, caused these findings. This is actually not the case as shown in Figure 9. Carbon emissions and cost are in this case very close for both kinds of blinds because the blinds tend to be lowered for glare protection during the winter and shoulder seasons (Figure 7).

Going forward the authors hope that others will adopt the reference office for the reasons and purposes listed in the introduction. To facilitate this process, example reference offices for different WWRs can be downloaded from the authors' institutional web page. While the authors are agnostic as to what simulation environment the reference office is being used with, it is evident that the environment should be able to handle manually controlled electric lighting and shading systems and that these systems are being treated in exactly the same way within the daylighting and thermal simulation. Apart from the underlying simulation method, a key concern for the authors is that meaningful performance metrics – comparable to the ones presented above – are being used.

A political sticking point may be the suggestion to use Boston as one of several reference locations in future studies to facilitate cross-study comparisons. This suggestion may seem overly self-serving since the authors' home institutions are located in Boston. In favor of this choice it is worthwhile noting that Boston has a challenging and instructive climate for facade design due to its pronounced summer and winter seasons.

The reference office may obviously be expanded to include skylights in which case the roof would become an external surface with a suggested R value of 0.273W/m^{2}K (ASHRAE 2007) to be in consistent with the façade.

CONCLUSION

This paper proposes and attempts to promote a standardized reference model and simulation analysis framework for daylit spaces. Simulation results for different WWRs show that a comprehensive and integrated analysis of daylight availability, occupant comfort and energy use may offer new insight into longstanding assumptions such as that large WWRs necessarily constitute an environmental liability. The shortcomings of such façade designs rather seem to be related to occupant comfort.

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