Adapting the Residential Daylight Score for Arid, Hot, and Humid Climates

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Abstract

Access to direct light is often considered a desirable quality in residential architecture. A novel daylighting performance metric called the Residential Daylight Score (RDS) has been suggested for cold and temperate climates to monitor diurnal and seasonal fluctuations in both daylight and access to direct light. However, direct light can significantly influence heating and cooling loads, and more research that correlates direct light with its thermal contributions is needed to make daylighting recommendations for warmer climates. As of now, residential daylight evaluation remains difficult in arid, hot, and humid climates, in which the effect of direct light on cooling loads is the largest. The authors juxtapose access to direct light with thermal and daylighting contributions across 14 different climate zones. The authors then propose a climate-based schema that considers thermal implications of daylight in residential architecture to adapt the RDS for use in warmer climates.

Introduction

The benefit of direct light in residential architecture has been long discussed in the European context. Since the beginning of the early twentieth century, architectural design guidelines, such as those by Neufert (Neufert & Neufert, 2012), have emphasized that domestic programs should be oriented toward the changing direction of direct light throughout the day. Several European countries provide regulations or guidelines to stipulate that each residential unit have access to direct light (German Institute for Standardization, DIN., 1999), which is regarded as an essential qualitative parameter for passive heating in dense urban neighborhoods with limited solar exposure on the façade (Strømman-Andersen & Sattrup, 2011). Even in warmer climates, access to direct light significantly influences the efficiency of vitamin D synthesis in the human body. Studies show that changes in contemporary Middle Eastern housing design that omit private outdoor spaces, such as courtyards, can be directly correlated with Vitamin D deficiencies in the female population (Fonseca, Tongia, el-Hazmi, & Abu-Aisha, 1984; Alagöl et al., 2000). Direct light is also needed to create physiologically and visually stimulating luminous environments (Andersen, Mardaljevic, & Lockley, 2012; Rockcastle & Andersen, 2014). As evident through these benefits, evaluation techniques that acknowledge the

positive effects of direct light in the residential setting are needed.

Residential Daylight Score

The *Residential Daylight Score* (RDS) was introduced as the first residential architecture-specific daylighting performance metric (DPM) that rewards the incidence of direct light (*Direct Light Access*, DLA) and evaluates general daylight supply (*Residential Daylight Autonomy*, RDA) (Dogan & Park, 2017; Dogan & Park, 2018). To account for seasonal and diurnal fluctuations in daylight, both the RDA and the DLA are evaluated in 12 timeframes (4 seasons and morning, noon, and evening). For each timeframe, the RDA evaluates whether a residential unit receives sufficient daylight ($\geq 300\text{lx}$) for 50% or more of daytime hours, based on thresholds for the *Spatial Daylight Autonomy* (sDA) (IESNA, 2012). The DLA evaluates the duration of direct sunlight access in a residential unit for each of the 12 timeframes. Finally, a composite RDS score is computed, with a maximum of 24 points (Figure 1). As the RDS assumes the presence of direct light in the interior to be beneficial, it was recommended for use only in cold and temperate climates, where passive solar heating is desirable and overheating in summer months is less of a concern.

Direct Light, Cooling Loads, and Glare

Because of its potential to increase cooling loads during warm months and impact occupant comfort (Uttinger & Wasley, 1997; Bennet & O'Brien, 2017), expectations and occupant response to direct light will differ in warmer climates. Intuitively, the value of direct light on an autumn day in Anchorage is much higher than that on the same day in Miami.

However, much of the research addressing the negative impacts of direct light have focused on completely blocking out direct light from the interior (typically

Figure 1: Residential Daylight Score

office spaces) to reduce visual glare, either with view-based glare probability metrics (Wienold & Christoffersen, 2006; Wienold, 2009; Jakubiec & Reinhart, 2012) or floor-plan-based oversupply metrics (Nabil & Mardaljevic, 2005; Mardaljevic, Andersen, Roy, & Christoffersen, 2011; IESNA, 2012). However, glare may be a less serious problem in the residential context, as occupants have an increased ability to change their orientation and posture and to control the shading in their environments (Jakubiec & Reinhart, 2012; Xue, Mak, & Cheung, 2014). In many cases, overheating due to direct light is a larger concern to residents than visual glare (Bennet, O'Brien, & Gunay, 2014).

Meanwhile, other studies have acknowledged the importance of balancing daylight (and more specifically, direct light) with its thermal impacts, and various proposals have been made to present the two kinds of data side-by-side (De Groot, Zonneveldt, Paule, & SA, 2003; Franzetti, Fraisse, & Achard, 2004; Hviid, Nielsen, & Svendsen, 2008). Reinhart and Wienold have proposed a "daylighting dashboard" that separately evaluates the daylight autonomy, occupant comfort (visual glare and view), and energy costs of space, modeled both with and without blinds (2011). Strømman-Andersen and Sattrup have noted that increased urban density moderately increases heating energy loads due to decreased exposure to direct light (2011). Kleindienst and Andersen have proposed three side-by-side, goal-based metrics that evaluate illuminance, glare, and solar heat gain (2012). Other studies address the effects of different kinds of shading schedules and thresholds on the artificial lighting, cooling, and heating energy loads of interior space in a specific climate (Nielsen, Svendsen, & Jensen, 2011; Shen & Tzempelikos, 2012).

Many of these studies and metrics acknowledge that daylighting performance must be understood not only in terms of providing sufficient daylight supply but also in the increase in cooling loads due to passive solar heat gain. However, a broader consensus on how to evaluate direct light in dwelling units with respect to its thermal impact still needs to be found.

Exhaustively defining the relationship between daylight performance and thermal implications is a difficult task, due to a large number of parametric possibilities in defining the experimental space, its construction and fenestration type, and other geometric variables. Nevertheless, the authors propose an energy simulation-based framework to study this relationship across 14 major climate zones and to inform a proof-of-concept adaptation of the DLA so that direct light in an apartment is considered beneficial only when it either decreases heating energy loads or does not increase cooling loads.

Methods

The authors indicate 14 climate zones defined by ASHRAE 90.1 2013 (ASHRAE, 2014) (Table 1). For each climate zone, example cities according to ASHRAE definitions and their corresponding latitudes are listed.

Table 1: ASHRAE climate zones

Zone	Climate Zone Name	Example Cities	Latitude
1A	Very Hot-Humid	Miami	25°47'N
		Singapore	1°17'N
2A	Hot-Humid	Houston	29°46'N
		Hong Kong	22°17'N
2B	Hot-Dry	Phoenix	33°27'N
		Cairo	30°3'N
3A	Warm-Humid	Atlanta	33°45'N
		Tel Aviv	32°04'N
3B	Warm-Dry	Los Angeles	34°03'N
		Mexico City	19°26'N
3C	Warm-Marine	San Francisco	37°47'N
		Cape Town	33°56'S
4A	Mixed-Humid	New York	40°40'N
		Seoul	37°34'N
4B	Mixed-Dry	Albuquerque	35°07'N
4C	Mixed-Marine	Seattle	47°37'N
5A	Cool-Humid	Chicago	41°53'N
		Munich	48°08'N
5B	Cool-Dry	Denver	39°44'N
6A	Cold-Humid	Minneapolis	44°59'N
		Moscow	46°44'N
6B	Cold-Dry	Helena	46°36'N
7	Very Cold	Anchorage	61°13'N

The authors create a shoebox with the dimensions of 6m x 10m x 3m and a floor area of 60m² as the test space. The shoebox has a single South-facing window. All surfaces, except the façade, are adiabatic. A fully conditioned space with a low air change rate (ACH = 0.3) and no natural ventilation is assumed. While the lack of natural ventilation may result in an over-estimation of cooling loads, the creation of a nearly airtight design space allows the calculation of pure (or "theoretical") heating and cooling loads solely based on climate, construction, and geometry. Potential cooling by natural ventilation would thus not be considered in this study.

For all climates, 4 levels of window-to-wall ratios (WWRs) are tested: 10%, 30%, 50%, and 70%.

For all WWRs, both "heavy" (concrete/masonry) and "light" (metal/timber frame) constructions are employed to account for differences in thermal loads. For each construction type, ASHRAE-defined U-values are used (ASHRAE, 2014) (Table 2).

4 shading types are then employed for all construction types. There is currently a lack of consensus on simulating residential blind usage. Therefore, sDA specifications for blind usage as specified by LM-83 (IESNA, 2012) were employed as a proxy. For a floor area of 60m², interior blinds must be drawn for all hours during which 5 or more of the floor grid sensors receive

1000lx or more of direct light. The 4 shading types (Table 3) include: An external shade that completely blocks the incidence of direct light in the interior; no shading whatsoever; interior blinds according to the sDA protocol; and a 1m balcony extrusion (a common feature in residential architecture) with interior blinds according to the sDA protocol.

Table 2: Heavy mass vs. light mass construction

Mass Type	Constr. (exterior to interior)	Façade U-val. (W/m ² K)	Façade Heat Capacity (kJ/m ² K)	Glazing Specification
Heavy mass	20mm Gypsum / 20-109mm Foam Glass Insulation / 300mm Concrete / 20mm Gypsum	U-0.404-0.857	731.4-738.6	U-1.820-2.840, Tvis 0.65, SHGC 0.27
Light mass	20mm Gypsum / 83-205mm Foam Glass Insulation / 20mm Gypsum	U-0.248-0.533	52.1-64.0	U-1.820-2.840, Tvis 0.65, SHGC 0.27

Table 3: Shading types

Shading Type	Shading Condition
Type A	External shade that completely blocks direct light
Type B	No shading
Type C	Dynamic interior blinds (sDA protocol)
Type D	1m extrusion above window + Dynamic interior blinds (sDA protocol)

In total, 448 shoeboxes (14 climate zones x 4WWRs x 2 constructions x 4 shading types) are created. The authors acknowledge that this is only a preliminary set of variables; an expansion of variables to include other orientations and glazing layouts is eventually necessary.

The 448 shoeboxes are tested for percentage of daylight floor area (defined by the sDA and RDA), heating energy loads, theoretical cooling energy loads, and electric lighting energy loads. An electric heat-pump with a coefficient of performance (COP) of 3 is assumed for heating and cooling loads. *DIVA4* is used for daylighting simulations (Solemma LLC., 2016), while *Archsim* is used for thermal simulations (Dogan, 2013). A summary of the workflow is found in Figure 2.

Daylighting and energy loads are summarized using the 12 time-bins from the RDS (Table 4) to facilitate a better understanding of seasonal and diurnal differences. Schedules for apartment occupancy, heating and cooling, electrical lighting, and equipment follow those of the U.S. Department of Energy (DOE) *Reference Buildings, Midrise Apartment, v. 1.4 7.2* (Department of Energy, 2004). All geometry, construction, and simulation parameters are provided in the Appendix.

Table 4: Diurnal and seasonal analysis timeframes that produce the 12 time-bins

Morning	Noon	Evening
Sunrise-11	11-15	15-Sunset

Spring	Summer	Fall	Winter
Feb/07-May/06	May/07-Aug/06	Aug/07-Nov/06	Nov/07-Feb/06

Results

Figure 3 shows the impact of direct light on daylighting, heating loads, cooling loads, and electric lights loads through a comparison between no direct light in the interior (Shading Type A) to full exposure to direct light, with no exterior shading or interior blinds (Shading Type B).

Figure 4 shows a close-up of *Heavy Mass: 50% WWR: Heating Load Changes: Winter* as an example for how the chart is to be read: As the climate zones become colder, direct light further reduces heating loads (decrease shown in green), particularly during morning hours. The biggest reduction in this condition is seen during morning hours in the Cool-Dry climate (Denver, 39°44'N), with a decrease in heating loads by

Figure 2: Workflow: Shoebox combinations and testing metrics

Figure 3: Changes in daylit floor area, heating loads, cooling loads, and artificial lighting loads by fully admitting direct light (i.e. transition from Shading Type A to Shading Type B).

3.8/kWh/m²/year. In Very Cold climates (Anchorage, 61°13'N), however, there is a smaller reduction of heating loads, as thermal losses through the glazing are larger than thermal gains by direct light. The results in Figure 3 confirm a number of intuitive assumptions:

First, admitting direct light into the interior dramatically increases the daylit floor area, particularly during noon hours (given the southern orientation of the shoebox). For example, a shoebox with a 30% WWR in a Cool-Humid climate (Chicago; 41°53'N) will see an increase of more than 50% points in daylit areas during noon hours across the year (Figure 3-a); that is, during spring noon hours, there is an increase from 10% of the floor area being daylit to 64% of the floor area being daylit (thus +54% points), and so forth. During morning and evening hours throughout the year in that climate, there will be moderate increases in the daylit area, except for winter evenings, during which there is an increase of only 15% points (Figure 3-a). The increase in daylit floor area will also slightly reduce artificial lighting loads, particularly during summer evenings and to a lesser degree in spring and fall evenings.

Second, direct light in the interior will decrease heating loads, particularly during spring and winter months in mixed to very cold climates. Increased WWR further reduces heating loads due to increased admittance of direct light in the interior. Similar trends, although slightly diminished, are observed in light-mass construction as well. For example, a shoebox with heavy construction and 50% WWR in a Mixed-Humid climate (New York, 40°40'N) sees heating loads reduced by 2.5, 1.0, and 1.4 kWh/m²/year respectively during winter morning, noon, and evening (Figure 3-b). In a light construction of the same parameters, the heating loads are reduced by 1.9, 0.9, and 1.1 kWh/m²/year respectively during the same time-bins (Figure 3-c).

Third, direct light in the interior will increase theoretical cooling loads throughout all climates, although during different seasons. Very hot to mixed climates will see heightened increases in cooling loads in winter months, during which solar altitude is lower. For example, a shoebox with heavy construction and 70% WWR in a Hot-Dry climate (Phoenix, 33°27'N) sees direct light increase theoretical cooling loads by roughly 3 to 5 kWh/m²/year during winter noon and evening (Figure 3-e). Direct light will cause less increase in summer months when solar altitude is high: 0.2, 0.3, and 0.1 kWh/m²/year respectively during a summer morning, noon, and evening (Figure 3-d). In cool to very cold climates, the increase in cooling loads is mostly limited to the summer and fall. Similar trends are observed in light-mass construction, with the notable difference that increases in cooling loads are shifted back toward the noon and evening hours across all seasons.

Discussion

Annual Changes in Energy Loads: Cost vs. Benefit

Figure 5 shows changes in annual loads in “heavy mass” shoeboxes as a result of the transition from no direct light (Shading Type A) to varying degrees of direct light

Changes in Heating Loads (kWh/m²/y):

Figure 4: Close-up: Changes in heating loads as a result of admitting direct light (Shading Type A to B) for Heavy Mass: 50% WWR: Heating Load Changes: Winter

Figure 5: Annual changes in heating, cooling, and electric lighting loads as a result of admitting direct light (Shading Type A to Types B,C,D)

(Shading Types B,C,D). The total energy loads represent the overall benefit or cost of direct light in the interior. Across all WWRs, direct light in the interior will increase total energy demand in very hot to warm climates, despite decreases in electric lighting loads. An increase in WWR will again intensify this trend. Direct light becomes a benefit in most mixed to very cold climates, due to a combined decrease in heating and electric lighting loads. For conditions with no shading whatsoever (shading type B), the most increase in total

energy loads is in 70% WWR, Hot-Dry climates (more than 20 kWh/m²/year; Figure 5-a), while the largest reduction is found in 70% WWR, Cold-Humid climates (around 10 kWh/m²/year; Figure 5-b). However, interior blinds (Shading Type C) will increase total energy loads in most climates (even mixed climates), as electric loads decrease only slightly (or even slightly increase). The said shoeboxes will see a respective increase of nearly 25 kWh/m²/year (Figure 5-c) and a decrease of only 5 kWh/m²/year (Figure 5-d) with Shading Type C.

Of course, simply examining the total annual increase or decrease in energy loads is a binary approach to the problem. Thus, seasonal and diurnal analysis is still necessary to understand when specifically direct light is thermally harmful.

Adapting the Direct Light Access (DLA) Score

Using this information, the authors select 6 residential projects across various climates (Figure 6) from an existing set of building models, taking 20 apartment units from each project, to assess the impact of energy demand consideration in the calculation of the Direct Light Access (DLA) score.

As of the current RDS, the DLA gives a full score for a time-bin only if there is a daily average of 2 or more hours of direct light in the interior during that time-bin. Partial scores are possible, in the case that the 2 average daily hours are not met. As there are 12 time-bins, the maximum DLA score is 12. As an initial exploratory adaptation, the authors suggest that all time-bins in which direct light increases cooling loads *and* does not reduce heating loads be excluded from the DLA analysis. Thus, all time-bins during which direct light is not useful for thermal purposes would be excluded from the DLA score.

Figure 7 shows the DLA analysis of apartment units in each of the 6 residential projects. The analysis is across all 12 time-bins, and the y-axis reports the average daily hours of direct light for each time-bin. All time-bins that are considered inappropriate for DLA evaluation – i.e. time-bins in which direct light will negatively impact

Figure 6: Six residential projects for DLA adaptation

Figure 7: DLA analysis of apartment units in each of 6 residential projects. Y-axis reports average daily hours of direct light per time-bin. All time-bins that are considered inappropriate for DLA evaluation are shaded out.

cooling loads and will not reduce heating loads – are shaded out. As a result, for example, none of the time-bins in the Hot-Humid climate (given Heavy Mass, 30% WWR) will be appropriate for DLA analysis. That is, direct light in the interior will always be harmful in that climate. In such case, exterior balconies would be recommended, as direct light is still vital for various physiological benefits (Fonseca, Tongia, el-Hazmi, & Abu-Aisha, 1984; Andersen, Mardaljevic, & Lockley, 2012). In Mixed-Humid and Cool-Humid climates, on the other hand, only the summer and fall time-bins would be inappropriate for DLA analysis.

Future Steps

The current workflow is a proof-of-concept that is based on simulation data of South-facing shoeboxes. Other orientations and room configurations (such as corner spaces with two facades) need further consideration. East- or West-facing spaces, for example, would likely result in higher cooling loads in the morning and the evening. Further, modeling blind use in residential architecture remains challenging and requires more research as to whether either the LM-83 blind model or a thermally-driven model is adequate. Possibly, an altogether new model that also considers views and privacy concerns, for example, may be needed.

Conclusion

While direct light access is widely regarded as a qualitative benefit, consequential heat gains may be undesirable in warmer climates. In order to understand the presence of direct light and its impact on heating, cooling, and electric lighting energy loads, this study establishes an EnergyPlus- and Radiance-based simulation framework to identify diurnal and seasonal timeframes during which direct light is either a benefit or a cost in terms of energy loads. The study analysed 448 shoeboxes of varying WWRs, construction types, and shading conditions across 14 climate zones. It is proposed to utilize the presented framework to adapt the DLA so that direct light is rewarded only when there are no negative thermal implications, expanding the applicability of the RDS to a larger variety of climates.

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Appendix

Table A1: Surface reflectance and window transmittance

Surface Type	Refl. / Tvis
Ceiling	70%
Floor	20%
Interior Wall	50%

Glazing (Double Pane, Low-E)	65%
(When applicable) Exterior Shading	35%
Outside ground	20%

Table A2: Radiance parameters

aa .15	ab 5	ad 2048	ar 512	as 1024

Table A3: Interior Dynamic Blinds Parameters

Min. Number of Sensors for Blind Trigger	5
Sensor Spacing	0.6m
Sensor Min. Distance from Window	0.1m
Sensor Max. Distance from Window	10.0m
Roller shade total transmission	4%
Roller shade direct transmission	1%
Roller shade total reflection	41%

Table A4: Zone Loads

People: Density	0.0283 p/m2
People: Schedule	Department of Energy reference buildings, midrise apartment, v. 1.4 7.2: APT_OCC_SCH
Equip: Loads	5.38 w/m2
Equip: Schedule	Department of Energy reference buildings, midrise apartment, v. 1.4 7.2: APT_EQP_SCH
Lights: Loads	3.88 w/m2
Lights: Target	300 lx
Lights: Dimming	Continuous
Lights: Schedule	Department of Energy reference buildings, midrise apartment, v. 1.4 7.2: APT_LIGHT_SCH
Heating: Setpoint	21.1 C
Heating: Av. Schedule	All On
Cooling: Setpoint	23.9 C
Cooling: Av. Schedule	All On
Hum: On/Off	On
Hum: Bounds	20-80%
Mechanical Ventilation: On/Off	Off
Natural Ventilation: On/Off	Off
Infiltration	0.3 ACH
Hot Water Peak Flow (l/h/person)	1.667
Coefficient of Performance (H/C)	3
Primary Energy Factor (H/C, Lighting)	2.2