Parametric study of window attachment impacts on building heating/cooling energy consumption

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Abstract

We present a parametric study of window attachment effects on building heating/cooling energy consumption. Commonly used operable window attachment types such as venetian blinds, roller shades, and cellular shades, in addition to fixed panels and solar screens, are investigated. Nine window attachment energy performance related parameters are chosen and varied, resulting in a total of 9072 combinations for each window attachment type and climate zone for the parametric study. The optical and thermal properties of each window and attachment combination are calculated in Berkeley Lab WINDOW program before being exported to EnergyPlus utilizing the bi-directional scattering distribution function (BSDF) fenestration model. The annual cooling and heating energy use of each window and attachment combination are simulated in EnergyPlus with a two-story residential building, based on the Department of Energy (DOE) typical residential building model and 1998 International Energy Conservation Code (IECC) vintage. New annual energy performance (AEP) indices are being developed for energy rating of window attachments. Here they are used as a metric for exploring the effect of attachment parameters on building heating/cooling energy use. Based on sensitivity analysis results, key parameters by window attachment type that have significant impacts on building heating/cooling energy use in cooling-dominated, heating-dominated and mixed climate are identified. The compound sensitivity in calculated AEP values caused by measurement uncertainties of input parameters are also calculated to help guide the window Attachment Energy Rating Council (AERC) in the determination of required measurement precision when rating the AEP of window attachments.

Introduction

The U.S. buildings sector, including residential and commercial buildings, accounted for approximately 40% of United States primary energy consumption and more than 70% of the electricity energy in 2014. This is the single largest energy-consuming sector in the nation (MER, 2015). The long-term and ambitious objective of the Department of Energy's (DOE) Building Technology Office (BTO) is to reduce the energy use intensity of homes and commercial buildings by 50% or more by 2030 through the application of cost-effective building efficiency technologies (BTO, 2016). Space heating and cooling were responsible for 43% of U.S. residential building primary energy consumption (equal to 9.37 quads of energy) (BEDB, 2011). Windows account for a large portion of energy use for space conditioning. It has been estimated that 30% of the energy used to heat and cool all buildings in the U.S. is lost through inefficient windows (Arasteh and Selkowitz, 2006).

In this context, there is large energy saving potential through improved energy efficiency of cost-effective technologies within window systems. Window coverings have been used by humans ever since we created openings in building envelopes. They were in use even before of advent of glass. It served to provide shelter from weather and privacy for building occupants, while allowing view, fresh air and egress through operable nature of these coverings. For the most part, modern window coverings and attachments, referred here as window attachments, are primarily designed for comfort, privacy and aesthetics. However, window attachments used in conjunction with quality energy efficient windows can play a complimentary role to save significant energy. Previous study has shown that the external roller blind and internal textile roller blind can save about 45% and 33% of energy savings, respectively, during heating seasons (Oleskowicz-Popiel and Sobczak, 2014). An experimental study in Montreal reported that the use of automated venetian blinds can decrease the energy cost by 30% in winter and by 50% in summer (Rheault and Bilgen, 1990). Similar cooling energy saving potential was reported for controlled outdoor blinds in Toronto (Nikoofard et al, 2014). Firlag et al. (2015) analyzed the control algorithms for dynamic windows for residential buildings and concluded that using of automated shading with proposed control algorithms can reduce the site energy in the range of 11.6–13.0%.

To simulate the energy saving performance of window attachments, several different approaches have been studied and developed. The primary focus of these works has been the experimental measurement, simulation, and simplified model development. Existing experimental work includes Garnet et al. (1995), Fang (2001), Naylor et al. (2002a), Naylor et al. (2002b), Collins and Harrison (2004a), Cuevas et al. (2010) and Clark et al. (2013). Simulation and simplified model development is included in the work

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of Ye et al. (1999), Collins (2004), Shahid and Naylor (2005), Marjanovic et al. (2005), Oosthuizen et al. (2005), Naylor and Shahid (2006), Wright (2008), Laouadi (2009), Roelevelld et al. (2010), and Hart et al. (2016). From the above literature review, we find that the energy saving potential of window attachments not only depends on the shade types, but also depends on the specifications of shade materials. Due to the wide variety of window attachment solutions and material characteristics, energy savings of window attachments vary significantly which makes customers confusion. However, previous studies mainly focused on evaluating single parameter's impact on the energy saving performance, rare research has been done to simultaneously evaluate the impacts of the overall indispensable parameters and to rate the energy performance of different attachments. As a consequence, even though some high performance attachment products are really available today, the researchers and customers can't distinguish their energy saving benefit quickly due to a lack of quantitative evaluation system. Thus, a complete parametric study and a fair performance rating and comparison index are essential to quantify their energy performance and such that to facilitate their rapid market adoption. In addition, a complete parametric study is also beneficial to re-engineer and enhance existing products to dramatically improve their performance, both in terms of intrinsic properties and in operations.

In this context, this paper presents a parametric study of window attachments on the annual building heating/cooling energy consumption with the goal to find key parameters that significantly affect window energy consumption. The results of this study will be utilized by the window Attachment Energy Rating Council (AERC) to develop an effective energy rating, including the determination of rules for window attachment product grouping, and to devise an appropriate testing methodology for material properties. By knowing the importance of each thermo-physical and optical property on the window attachment energy performance, manufacturers can focus on important properties to optimize their design for energy efficiency.

Building model

An EnergyPlus model of a typical two-story residential building with two windows per orientation and per floor, for a total of 16 windows, was developed. Figure 1 shows the schematic diagram of the building model.

This model was based on DOE's residential building model (RPBM, 2012), with insulation and infiltration levels corresponding to the requirements of International Energy Conservation Code 1998 (IECC 1998). The choice of a 1998 vintage of IECC energy code was done as a representative of the average of both existing and new constructions. Windows are equally distributed on each orientation, so that the effects of orientation are averaged out. Houston, Minneapolis and Washington DC, are chosen to represent the hot, cold and mixed climates, respectively. The detailed building model information is listed in Table 1.

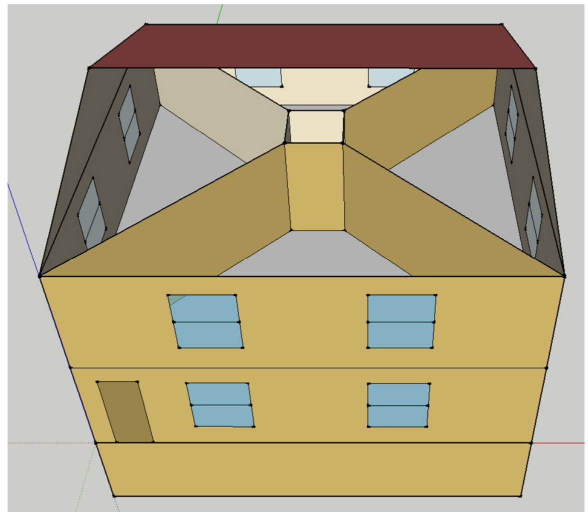

Figure 1: Schematic diagram of the building model

Table 1: Building model input information

Parameters	Setting values
Dimension of building	10.56 m x 10.56 m x 2.6 m x 2 stories
Foundation	Unheated Basement for Minneapolis, slab on grade for Houston and Washington DC
Heating and cooling	Heat pump for Houston; gas furnace and air conditioning for heating and cooling in Washington DC and Minneapolis
HVAC efficiency	AFUE= 0.78 for Gas furnace heating; HSPF=6.8 for Air-cooled heat pumps heating mode; SEER=10.0 for Air-cooled air conditioners and heat pumps cooling mode
Window area	1.4 m x 1.5 m for each window; WWR=15%
Thermostat Settings	Heating: 21.1℃ (70 F) Cooling: 23.9℃ (75 F)
Internal loads	Refer to the DOE's residential building simulation model (RPBM, 2012)
Envelope insulation	Refer to IECC 1998
Air infiltration	ACH50=7 for Minneapolis ACH50=8 for Washington DC ACH50=10 for Houston
Baseline window:	Double clear glazing with wood fixed frame; U-factor: 2.68 (W/m^2k), SHGC: 0.60, Visible Transmittance: 0.64, Air Leakage: 2.0 cfm/sf.
Occupants	3
Weather data	TMY3 of Houston, Washington DC and Minneapolis

Window attachments parameters and operation

The most commonly utilized window attachments in the US are analyzed, including venetian blinds (VB), solar screens (SS), roller shades (RS) and cellular shades (CS). Products are mounted on both exterior and interior side, where applicable (e.g., cellular shades are not available as exterior option, so only interior mount was considered). Attachments were modelled fully deployed to find maximum impact on energy performance, so whether they are operable or not, they were modelled in one fully deployed position.

To conduct the parametric study, nine parameters, listed in Table 2, were varied. In order to represent a broad range of different window attachment parameters, three different sets of values, were used for each window attachment parameter (low, medium and high). The low and high values were mostly determined by the lower and upper theoretical limits, respectively. These theoretical values do not necessarily represent current products, but might represent range of values of future products. Thus, they were chosen in this study for a full range of parametric analysis. The medium value of each parameter was selected based on a typical value for current mainstream products. Totally, a combination of 3^9 cases was initially created for each kind of window attachment. However, considering the physical nature of some parameters, such as the sum of emissivity and thermal IR transmittance cannot be larger than 1, and the sum of solar transmittance and reflectance cannot be larger than 1, some unreasonable cases were eliminated and the final combination of 9,072 cases was created for each type of window attachment in each city. There are 99,792 total cases for all window attachments and the three chosen climates.

Table 2: Parameters and different levels of value

Parameters (Units)		**Low value**	**Medium value**	**High value**
Emissivity 1 (0-1)		0.05	0.2	0.9
Emissivity 2 (0-1)		0.05	0.2	0.9
Thermal IR Transmittance (0-1)		0/0.05[1]	0.2	0.9
Solar Transmittance (0-1)		0.01	0.1	0.8
Solar Reflectance (0-1)		0.05	0.1	0.5
Thermal openness (0-1)		0	0.02	0.1
Conductivity (W/mK)	SS[2] and VB	0.05	1	160
	CS[3]	0.0025	0.025	0.635
	RS	0.025	0.2	160
Left & right gap (mm)		0	3	12
Top & bottom gap (mm)		0	3	12

Simulation methodology

EnergyPlus 8.5 was used in this study for annual building energy simulation. The optical and thermal characteristics of each window attachment case were determined with Berkeley Lab WINDOW and THERM software tools, with optical properties calculated using Bi-directional Scattering Distribution Function (BSDF) method. Calculated whole window optical and thermal properties were exported from WINDOW and later imported into EnergyPlus using IDF file format. Total of ~100,000 energy simulation runs were conducted.

Annual energy performance indices

New annual energy performance indices for window attachments were developed to evaluate the impact of each window attachment on the building cooling/heating energy consumption. Since the goal of an energy rating system is to be able to rank product performance in relative energy savings terms, the simulation process was used to extract the relative heating and cooling differences of each attachment when used over the same base case window. The annual energy performance indices of attachment for cooling (AEP_C), or for heating (AEP_H) , as shown in Eq.(1), are defined as the ratio of annual cooling/heating energy savings resulting from the addition of window attachment to the baseline window ($E_{B\text{-}S}$) to the annual energy use difference between the building with baseline window and building with "adiabatic" window ($E_{B\text{-}A}$).

$$AEP = \frac{E_{B-S}}{E_{B-A}} \quad (1)$$

where, $E_{B\text{-}S}$ is calculated by Eq.(2) and $E_{B\text{-}A}$ is calculated by Eq.(3).

$$E_{B-S} = E_B - E_S \quad (2)$$

$$E_{B-A} = E_B - E_A \quad (3)$$

As shown in Figure 2, E_A is the annual cooling or heating energy use of the house with "adiabatic" window; E_B is the annual cooling or heating energy use of the house with baseline window only; E_S is the annual cooling or heating energy use of the house with window attachment. For the "adiabatic" window model, a ultra-insulating window glazing system was defined that approximated an adiabatic (zero heat transfer) surface. SHGC and infiltration were both set to 0.

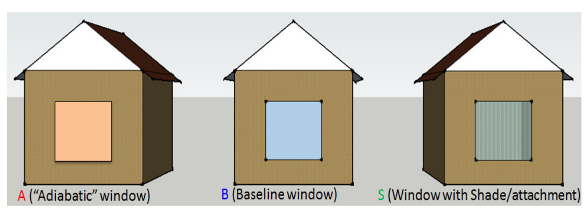

Figure 2: Schematic diagram of different window modelsThe annual energy performance index (AEP) is a ratio of energy saving potential of the window attachment to the energy use of the baseline window without attachment. The use of a non-dimensional AEP index instead of specific quantity of energy saving, allows for the simple impact comparison of window type, glazing characteristics, climate zone, and orientation. Thus, it is a more stable, effective and recognizable annual energy performance index. In addition, the AEP value can simply and directly reflect

[1] 0 for SS, RS and CS, 0.05 for VB
[2] SS: solar screen; VB: venetian blinds; CS: cellular shades; RS: roller shades
[3] assuming cellular shade thickness is 1 inch

the performance of the attachment compared to the window without attachment. Table 3 lists the ranges of AEP and the corresponding energy saving performance.

Table 3: Annual energy performance ranges and the corresponding performance

AEP ranges	Attachment performance
AEP < 0	negative impact on the annual energy performance of window ($E_S > E_B$)
AEP = 0	does not have any impact on the annual energy performance of window ($E_S = E_B$)
0 < AEP < 1	has a positive impact on the annual energy performance of window and saves a portion of energy ($E_S<E_B$); most of the attachments would be in this case
AEP = 1	makes the window system a zero net energy window ($E_S=E_A$); in other words, window system has NO energy impact on the house
AEP > 1	makes the window system a net energy producing window ($E_S > E_A$). The window is, therefore, better than an adiabatic surface.

Discussions and results analysis

Impacts of parameters on AEP

The results are presented in the form of the average annual energy performance (AEP) change in response to the low, medium, and high values of analyzed parameters for window attachments. First, one parameter is frozen, e.g. Emissivity 1, then the AEP for a fixed value of that parameter over all other parameters is averaged, (e.g. AEP (ε_1=0.05) = mean AEP of all runs with ε_1=0.05). A change in AEP is plotted vs. parameter change, treating a range of parameters as low, medium and high values, rather than their actual values. The above procedures were repeated for all varied parameters, all climates and all attachment types.

The impacts of each parameter on AEP of window attachments in different climates are illustrated in Figures 3 through 6. As shown in Figure 3, the solar reflectance and solar transmittance have the expected significant impacts on the annual cooling energy performance (AEP_c) with all four types of window attachments in Houston. Specifically, the window attachments' AEP_c goes up with increasing solar reflectance and declines with increasing solar transmittance. The variation of AEP_c is relatively small when the values of these two parameters change from low level to medium level, but significant from medium level to high level. The exterior solar screens with low solar transmittance produce very high AEP_c, about 0.9, which means that these solar screens are the most appropriate window attachments for cooling-dominated climate from the energy saving perspective. As expected, the results confirm window attachments with high reflectance and low transmittance are more suitable for application in cooling-dominated climates. Also, exterior mounted solar screens are superior to interior mounted shades for cooling-dominated climates. The impacts of each window attachment parameter on AEP_c in Washington DC are found in Figure 4.

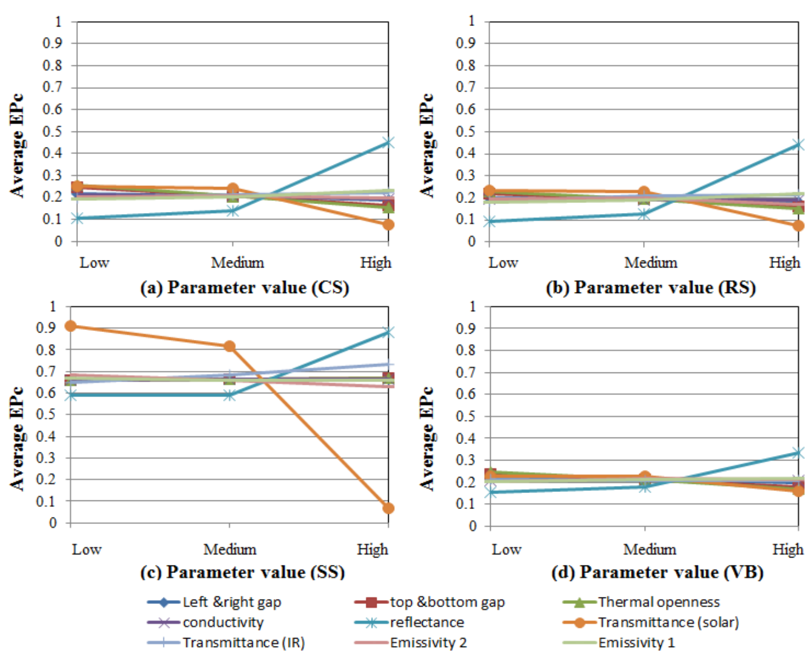

Figure 3: Impacts of different parameters on annual cooling energy performance in Houston; (a) interior cellular shades, (b) interior roller shades, (c) exterior solar screens, (d) interior venetian blinds

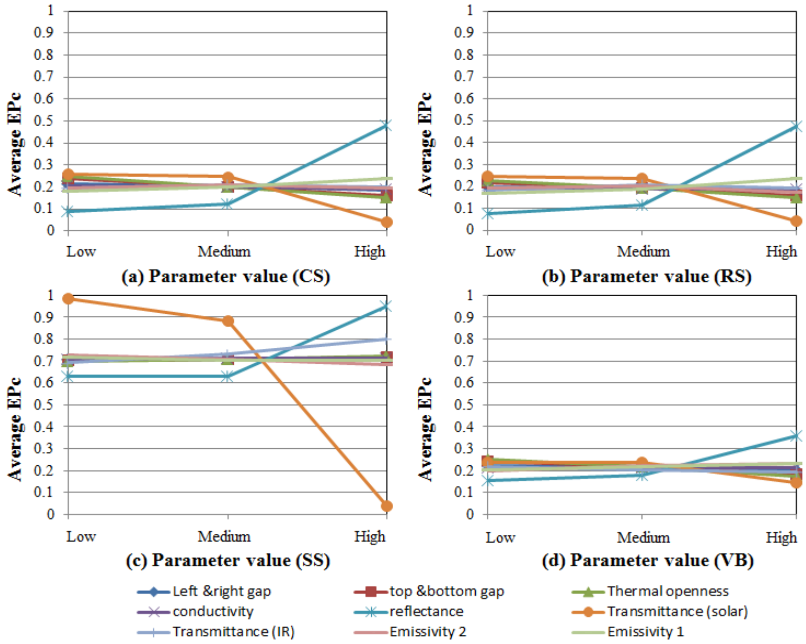

Figure 4: Impacts of different parameters on annual cooling energy performance in Washington, DC; (a) interior cellular shades, (b) interior roller shades, (c) exterior solar screens, (d) interior venetian blinds

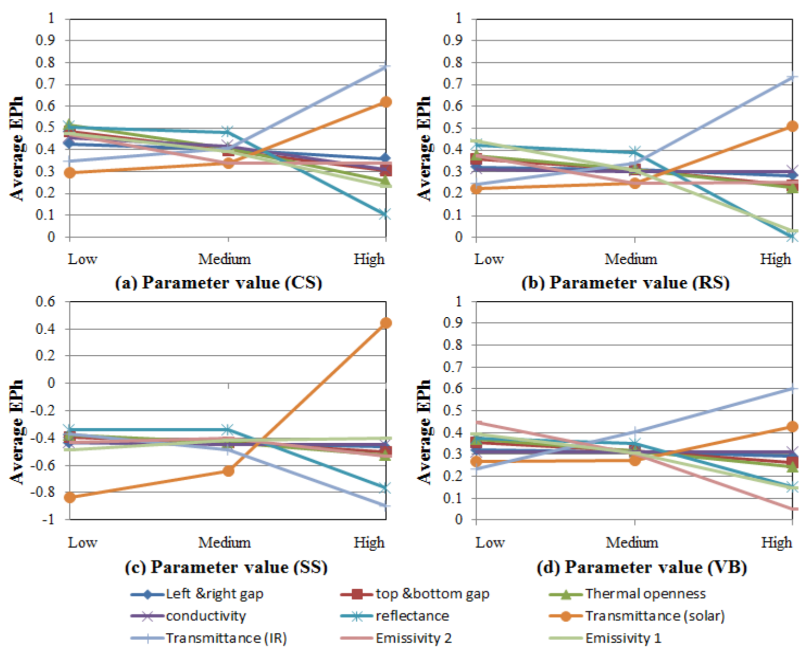

Figure 5: Impacts of different parameters on annual heating energy performance in Washington, DC; (a) interior cellular shades, (b) interior roller shades, (c) exterior solar screens, (d) interior venetian blinds

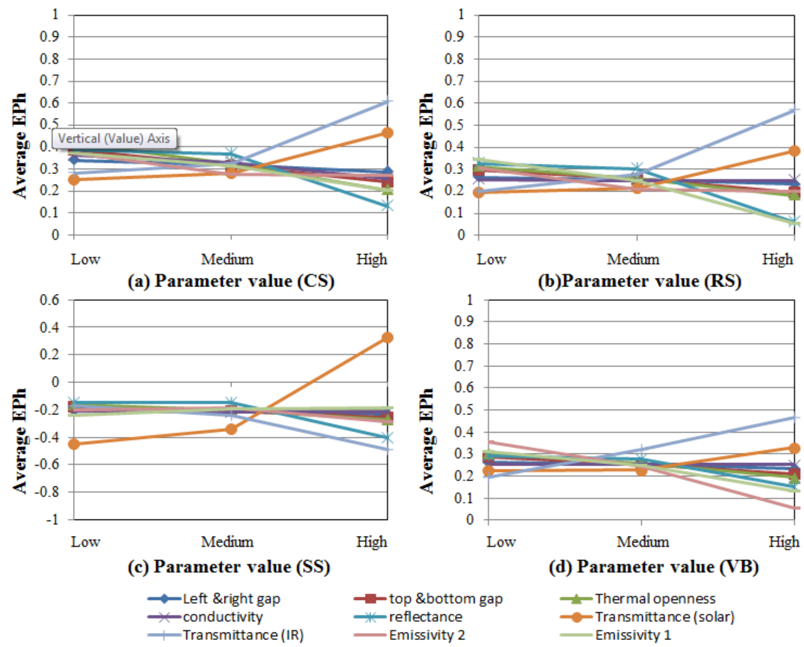

Figure 6: Impacts of different parameters on annual heating energy performance in Minneapolis; (a) interior cellular shades, (b) interior roller shades, (c) exterior solar screens, (d) interior venetian blinds

Figures 5 and 6 illustrate the variation of annual heating energy performance (AEP_h) of window attachments in Washington DC and Minneapolis, respectively. Solar reflectance and solar transmittance have significant impacts on the AEP_h for all four types of window attachments in the mixed and heating-dominated climates. The window attachments' AEP_h declines with increasing solar reflectance and increases with increasing solar transmittance. These trends are opposite to those of AEP_c in the cooling-dominated climate.

Increasing thermal infrared transmittance and emissivity 1 (the front surface emissivity) have significant negative impacts to AEP_h, with the exception of exterior mounted solar screens.

For exterior mounted solar screens, AEP_h is almost always less than 0 except the case with high solar transmittance, which makes sense from the perspective that the exterior window attachments block sunlight and reduce the solar heat gain in demand for the heating-dominated climate. These results confirm our expected outcome that window attachments with high solar transmittance, low solar reflectance, low conductivity, and low emissivity are more suitable for application in heating-dominated climates.

Sensitivity analysis of the parameters

The slope of AEP as a function of the individual parameters can be used as a measure of how sensitive AEP is to that particular parameter, i.e. how influential that parameter is in the calculation of the AEP. With that information it is possible to implement simplification rules for parameters that show little influence. The quantitative result can inform accuracy requirements for measurement techniques with parameters that have high influence on AEP. Calculation of the individual values is required to be able to calculate the compound sensitivity effect on the AEP value, something that would be important when deciding on the granularity of a rating system based on AEP values.

The slope of the line between low, medium and high values was calculated for each parameter as a measure of the impact on the total AEP for the individual parameters. This allows us to quantify which parameter was most impactful for a given combination of product and climate. The results for transmittance, reflectance, emissivity, and thermal openness were intuitive to interpret. For those parameters, the slope can be used to see the impact on AEP for a 0.01 change in the parameter, i.e. how much the absolute AEP value can be expected to increase or decrease if an individual parameter is varied. However, the conductivity spanned several orders of magnitude, from 0.001 to 160 W/mK, so it was not possible to characterize that parameter in the same way as the others and therefore it was excluded from Table 4.

Going through all the slopes for all product and climate combinations, we were able to identify the highest possible impact a parameter could have. A compilation of the impact on AEP as a function of ±0.01 change in the parameter is shown in Table 4. Values that are listed at 0.01 indicate that AEP is directly proportional to that parameter, values higher than 0.01 indicate that the change in AEP will be larger than the change in parameter, i.e. it is a highly influential parameter. Likewise, values lower than 0.01 indicate that change in AEP will be smaller than the change in the parameter, i.e. it is a less influential parameter.

Table 4: Highest recorded change in AEP for each product at a ±0.01 change in parameter value

Material Type	Openness Factor [OF]	Solar/Visible Transmittance [τ_S/ τ_V]	Solar/Visible Reflectance [R_S/R_V]	Exterior Emissivity [ε]	Interior Emissivity [ε]	Infrared Transmittance [τ_{IR}]
Exterior Shades ex. Exterior solar screens	±0.007	±0.02	±0.001	±0.001	±0.005	±0.011
Interior Blinds ex. Interior venetian blinds	±0.007	±0.001	±0.004	±0.006	±0.01	±0.001
Interior Shades (insulating) ex. Interior cellular shades	±0.013	±0.005	±0.008	±0.003	±0.001	±0.004
Interior Shades (non-insulating) ex. Interior roller shades, interior solar screens	±0.008	±0.003	±0.008	±0.008	±0.001	±0.004

Having the sensitivity isolated for each parameter it is possible to look at the compound sensitivity effect on the AEP. Assuming that each parameter is uncorrelated to the others the compound sensitivity can be calculated according to Eq. (4):

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \ldots + \left(\frac{\partial q}{\partial z}\delta z\right)^2} \quad (4)$$

where, q is the AEP, x,…z are the measured parameters and δx,…,δz are the corresponding random uncertainties for each parameter, and the partial derivatives $\partial q/\partial x, \ldots, \partial q/\partial z$ are the sensitivity values recorded in Table 4.

The true values for δx,…,δz will depend on the measurement method and quite possibly also the product studied, e.g. it is easier to accurately measure an openness of 0.00 than other values. To calculate the values in Table 5 a conservative estimate is made of how accurate common measurement methods would be on a majority of products. The values assumed were 0.03 for the emissivities, TIR, and reflectance, and 0.02 for transmittance and openness. The compound sensitivities of AEP, using the sensitivities in Table 4, were calculated and the results are listed in Table 5. The largest compound sensitivity is seen for AEP_h in Washington for external shades and panels.

Table 5: The calculated compound sensitivity of AEP for different shades and climates

Shade Type	CS	RS	SS	VB
AEP_c - Houston	±0.026	±0.024	±0.022	±0.014
AEP_c - Washington	±0.028	±0.027	±0.025	±0.016
AEP_h - Minneapolis	±0.030	±0.028	±0.035	±0.029
AEP_h - Washington	±0.041	±0.040	±0.057	±0.039

Conclusions

A sensitivity analysis was conducted to identify the impacts of different window attachment parameters on residential building annual heating/cooling energy performance utilizing a newly developed non-dimensional index of window attachment annual energy performance (AEP). This sensitivity analysis enabled us to quantify relative and compound effect for each of the nine studied parameters. The change of AEP versus parameter variation was illustrated in graphs to intuitively express the impacts of different design and construction parameters on window attachment performance in different climates.

For cooling climates and seasons, solar transmittance and interior vs. exterior mounting had largest impact on AEP. For heating climates and seasons, solar transmittance again had a large impact on AEP, however conductivity and emissivity were also important. These results confirm general expectations for energy savings potentials for these classes of systems but now provide a relative quantitative metric to these expectations.

Quantified slope, calculated as a derivative of AEP with respect to different parameter values, provided information about overall impact of the individual parameters on AEP. This sensitivity can then inform future rating implementation about required measurement accuracy and product grouping. Provided that future window attachment rating will likely include both cooling and heating energy performance, effect of individual parameter in AEP will be cumulative. For example, even though shading openness factor plays smaller role in cooling AEP, because it plays more significant role in heating AEP of interior shades, accuracy and importance of its determination will be high.

Having the sensitivity isolated for each parameter, it is also possible to look at the compound sensitivity effect on the AEP. This was calculated for all of the studied four types of window attachments. The largest compound sensitivity was seen for AEP_h in Washington for external shades and panels.

This quantitative evaluation will help guide the window Attachment Energy Rating Council (AERC) in the determination of required measurement precision and in guiding grouping rules development for simplification of ratings. Moreover, the methodology proposed in this paper will be refined and then used as the basis of rating the energy performance of window attachments for hot (cooling-dominated) and cold (heating-dominated) climates by AERC.

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