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Simplified metrics for advanced window systems. Effects on the estimation of energy use for space heating and cooling

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Abstract

Simplified metrics (U-value, g-value) are often used to energy use for space heating and cooling when conventional windows are adopted, but they are not fully capable of describing the thermophysical behaviour of more advanced windows. In this paper the impact of these metrics on the estimation of the energy use for space heating and cooling in case of a double skin façade is evaluate. The results of the investigation for one climate show that, even if the inaccuracy for a double skin façade is higher than for a conventional window, the inaccuracy is still acceptable in the preliminary design phase.

Keywords: Double skin façade; Metrics; U-value; g-value; Heating energy demand; Cooling energy demand; Building Performance Simulation.

1. Introduction

Double Skin Facades (DSFs) [1] are dynamic building envelope systems well-established in the market, and very popular solutions because they allow a "transparent" appearance of the building to be achieved without: i) imparting

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indoor visual, thermal, and acoustic comfort conditions, ii) requiring too high energy demand for cooling (and heating), and iii) enabling a more adaptive behaviour in the building envelope.
The thermophysical behaviour of DSFs is more complicated than that of conventional glazing systems (e.g. that of a double glazed unit, DGU), because of the heat removal/injection in the cavity, which makes so that the heat transfer phenomena through this glazed system are highly characterized by transient states. Validated numerical codes for DSF implemented in tools for building performance simulations are therefore necessary to correctly replicate the heat exchange between the inside and the outside of the building, when a DSF is installed. However, the use of conventional, steady-state performance metrics, such as U-value and g-value, are often required by technical regulations to prove the performance of such components. While U-value and g-value are performance indicators suitable for conventional windows, their applicability in case of DSFs is intrinsically questionable: U-value and g-value are metrics developed under steady state assumptions, a condition that is hardly seen in DSFs.

1.1. Background

In a previous study [2], the U-value and the g-value of both a conventional double glazed unit and of a mechanically ventilated DSF have been obtain through the application of a simple linear regression method to experimental data. These values have then been used to simulate the heat transfer through these systems assuming simplified, heat transfer equations, conventionally adopted in models for the calculation of energy use for space heating and cooling [3].
The simulated heat transfer values have then been compared against the experimental ones, leading to the following conclusions. On the one hand, synthetic metrics and simplified modelling may results in some errors even in case of conventional glazing systems, it is still acceptable to use these parameters if the glazing technology is a "simple" one. On the other hand, the adoption, in case of more advanced façade technologies, of U-value and the g-value, coupled with a simple heat transfer model, leads to considerable inaccuracies in the estimation of the heat flux and energy that cross the glazing surface. Notably, in the case of the mechanically ventilated DSF analyzed, simulated physical quantities under- or over-estimate experimental data by more than 25% for more than half of the time.

1.2. Aim of the paper

A significant under- or overestimate of heat transfer trough the DSF through the use of simplified metrics might not necessarily result in a likewise under- or overestimate of the energy demand for space heating and cooling, since heat transfer through the façade is only one of the component that affect the energy demand of a building.
On the one hand, it is important to remark that only through advanced simulation tools all the benefit of the adoption of DSFs can be more accurately accounted. On the other hand, it is also important to observe that the use of simplified metrics in the preliminary design phase is a very diffuse approach, and this can be effective if such metrics are effective in representing the behaviour of advanced facade systems.
The aim of the research presented in this paper is thus to complement and build upon the previous study [2], and to assess the impact of an under- or overestimated heat transfer (through a mechanically ventilated DSF, and through a DGU for reference purpose) over the energy demand for space heating and cooling. Such an assessment is important to understand whether, and to what extent, simplified metrics such as U-value and g-value can be used or not to simulate the performance of a DSF in the preliminary phase of the building design, when simplified simulation tools/methods are used to take main decisions on the building configuration.

2. Materials and methods

2.1. Workflow

In Table. 1 the workflow adopted in this investigation is shown. Such a workflow is repeated twice, once for the DSF and once for the reference DGU. In this paper, only steps 5-9 are presented; necessary, background information on steps 1-4 are only briefly given herewith, while more detailed facts can be retrieved from [2].
In short, starting from experimental data, normal distributions of U-value(s) and g-value(s) have been determined in order to construct a set of time-series with dynamics, normally distributed U-values and g-values. These time-series have been used in dynamic simulations to calculate energy use for space heating and cooling. The following data post-

processing has led to the determination of normal distribution of energy use for space heating and cooling, which is used as an indicator of the impact of simplify metrics on the energy use for space heating and cooling.

2.1. Glazing technologies and data from experimental analysis

The two tested glazing systems, used for the investigation presented in this paper, were: *i)* a double glazed (DGU) system (8/15/6 mm) made with an external reflective pane and an internal clear glass and installed and tested on an outdoor test cell facility (for reference purpose), and *ii)* a mechanically ventilated DSF, tested in a real building. Both the test sites were located in a temperate sub-continental climate in Italy, with a latitude of 45°, and had the same orientation (facing south). The façade was composed by an external extra-clear single glazing, a mechanical ventilated cavity (approx. 0.7 m) with a high reflective roller screen, and a low-e internal double glazing (4/12/4 mm) [4].
Following the experimental procedure described in [2], seasonal or annual values for the metrics U-value and g-value were found, as reported in Tab. 1, using a linear regression method to correlate two physical quantities. As far as the DGU is concerned, it was possible to find just one U-value representative for the behaviour in the different seasons, while three g-values were necessary to describe the system with a sufficient accuracy. As far as the DSF is concerned, three different U-vales were found, as well as three different g-values (though two of these, the winter and mid-season ones, are extremely close).

2.1. Determination of normal distribution functions and construction of time-series

According to the theory of measurement, when a quantity to be determined is measured several times, the individual measurements should distribute in frequency around the "real" value according to a normal distribution. In the previous study [2], the U-value(s) and g-value(s) have been determined for annual or seasonal periods.
However, when the U-value and g-value is continuously assessed, for example every hour or for sub-hourly time intervals, the total set of values recorded over a certain period should fit a normal distribution function, if the quantity (e.g. the U-value) under investigation is i) correctly measured and ii) physically meaningful. A well-measured, meaningful physical quantity is represented by a normal distribution characterized with a variance tending to zero, and with a good fitness (low RSME) with the frequency distribution of the measured values. A normal distribution characterized by a high variance corresponds instead to a wider spread of values, and thus to a badly measured quantity and/or to a quantity/metric that does not fully represent the physical phenomenon.

Table 1. Workflow of the research activity in steps.

Step	*Description*	*Availability*
1	Technologies and test procedures	[2]
2	Experimental data collection	[2]
3	Experimental data processing (LR method)	[2]
4	Determination of annual/seasonal U-value(s) and g-value(s)	[2]
5	Determination of normal distributions of U-value(s) and g-value(s)	this paper
6	Construction of (fifty) time-series with dynamic U-value(s) and g-value(s)	this paper
7	Annual simulations (fifty) for determination of energy use for space heating (E_h) and cooling (E_c)	this paper
8	Numerical data processing (normal distribution of E_h and E_c)	this paper
9	Determination of the impact of simplify metrics on space heating (E_h) and cooling (E_c)	this paper

Table 2. U-values and g-values for DGU and DSF, for different seasons, as determined in [2] through annual/seasonal linear regressions.

Glazing Type	**Double Glazed Unit (DGU)**		**Double Skin Façade (DSF)**	
Metric	*U-value* [W/m²K]	*g-value* [-]	*U-value* [W/m²K]	*g-value* [-]
Winter season		0.357	0.729	0.081
Mid-season	2.116 (all year)	0.319	0.694	0.080
Summer season		0.183	0.615	0.072

In this work, the fitness between the frequency of hourly values of U-value and g-value, and normal distribution functions (or in other words, the possibility to describe the series of U-values and g-values as normal distribution functions), has been used with a two-fold scope. One the one hand to evaluate the representativeness (and measurement correctness) of the parameter; on the another end to determine continuous normal function, to be later

used to construct sets of variable U-value and g-value time-series (for both the DSF and the DGU), showing the same distribution of U-values and g-values recorded experimentally over the corresponding period.
The determination of the correspondent normal distribution function for the frequency distribution(s) of U-value and g-value has been carried out by minimizing the RSME between the values of the experimental data series and the values of the continuous normal distribution function to be determined.
Fifty time-series with 8760 values (one each hour of the year) have been randomly generated for each glazed technology. Each time-series shows a random distribution, as far as each time-step is concerned, of U-value and g-value, but the overall distribution of each time-series follows the normal distribution determined as above explained.
Fifty series of variable U-value and g-value where necessary in order to carry out enough simulations, as explained in the following section, so that it was eventually possible to eliminate the effects of random distribution along the time-steps of the variable U-value and g-value in the series generated.

2.1. Simulations and numerical data processing

The building model used as a reference case for this investigation is the Bestest Case 600 [5], i.e. a rectangular room with two large south facing windows, equipped with an ideal heating and cooling system, with dual set-point. The simulations were ran with the typical meteorological year weather data of Torino, Italy.
The building model was equipped once (fifty annual simulations) with DGU, and once (fifty annual simulations) with DSF. Each time, a different variable U-value/g-value time-series was used to input the glazing characteristics. The use of variable U-values and g-values could not directly be implemented in the software tool (*EnergyPlus* [6]) used for dynamic thermal simulations, and some workaround solutions were thus necessary to achieve the desired simulations. Each of the fifty simulation (for each glazing technology) returned the annual energy use for space heating E_h [kWh/m^2] and energy use for space cooling E_c [kWh/m^2], and a set of fifty E_h and E_c values was then obtained for each glazing technology. These values were then analyzed in terms of frequency distributions, and the mean values and variances calculated. Moreover, frequency distributions normalized over the distribution's mean values were calculated for each energy use and each technology. This allowed a direct comparison between the results of the simulations with the two technologies to be carried out, and consequently the assessment of the impact of simplified metrics on the energy use for space heating and cooling.

3. Results and discussion

The results of the determination of normal distribution functions associated to experimentally measured U-values and g-values are presented in Table 3, and some examples of the comparison between experimental data and fitting normal distribution equations are illustrated in Figure 1. In the previous study [2], the annual U-value for the DGU was characterized with a very high coefficient of determination (> 0.91), similar and even higher than some of the correspondent ones for the U-values of the DSF. Conversely, the analysis through normal distribution function reveals herewith a variance (in percentage) for the U-value of the DGU approximately 1.5 times higher than that of the DSF. This is an unexpected finding, that might deserve further investigations.
The analysis of the g-values provides instead results that are in line with the previous investigation: the g-values obtained for the DGU show a variance (in percentage) that can be half of those obtained for the DSF, thus confirming that the g-values found for the conventional glazing system are of better quality and more representative of the phenomenon. However, it is important to notice that the g-values for the DSF are extremely low (lower than 0.10), due to a reflective roller shading always displaced in the cavity. These low values can lead to intrinsic difficulties in the measurements of the physical quantities involved in the g-value equation, and this can eventually result in a lower precision of the obtained value – even if the metric itself might still be representative for the physical phenomenon.
The analysis of the energy use for space heating and cooling (Figure 2) reveals that these values, calculated using a statistical approach that makes use of fifty simulations with different, time-dependent series for U-value and g-value, are distributed around a mean value with a normal distribution like function. From the comparison of the normalized annual energy use, it is clear that the distribution is slightly more spread (higher variance) in case of the DSF than when a conventional DGU is simulated, as far as the space heating is concerned (Figure 2 c). Conversely, the distributions for the two technologies are very similar when the space cooling is concerned (Figure 2 d), showing that the different representativeness of the g-value for the two technologies is not reflected with the same intensity when it comes to energy for space cooling – and to a lower extent, for space heating too. This fact can be probably explained

considering that the g-values for the DSF are very low, and approximately one fifth of the DGU's ones. Under these conditions, even a relatively large lack of representativeness of such a metric can have little impact on the energy use. Furthermore, it is important to highlight that for both the technologies, the maximum percentage variation from the mean value is in the range of ± 3 % and ± 1 %, for the space heating energy use and space cooling energy use, respectively (both in case of the DSF). This in turn means that even if the metrics are not fully representative of the behaviour of the system, their influence on the calculated energy use to climatize the building is very modest. On the one hand, this result may depend on the selected case study for the simulation (with relatively high interior gain other than the solar gain, and a window-to-floor area ratio of 0.125 – thus not a high glazed buidling), as well as on the glazed technologies adopted (both characterized by relatively – DGU – and very low – DSF – g-values). However, on the other hand, it is also reasonable to hypothesise that glazing systems with higher performance (such as DSF) contribute to lower energy use for space heating and cooling (as shown in Figure 2 a and b), and therefore a lower accuracy of their metrics has a lower impact than in the case of conventional, lower performance glazing solutions. Finally, it is worth mentioning that the simulations and the analysis are carried out in a specific climate, and the same investigation in different climates might result in (slightly) different results.

Table 3. *U-values* and *g-values* for DGU and DSF in terms of normal distributions fitting the experimental data. The variance σ of each normal distribution is expressed both in absolute units of measurement (W/m^{2}K or -) and (in brackets) as percentage of the mean of the distribution μ.

Glazing Type	**Double Glazed Unit (DGU)**				**Double Skin Façade (DSF)**			
Metric	*U-value* [W/m^{2}K]		*g-value* [-]		*U-value* [W/m^{2}K]		*g-value* [-]	
	μ	σ	μ	σ	μ	σ	μ	σ
Winter season			0.350	0.062 (17%)	0.723	0.032 (4%)	0.080	0.022 (28%)
Mid-season	2.205 (all year)	0.292 (13%) (all year)	0.300	0.060 (20%)	0.680	0.060 (9%)	0.090	0.030 (33%)
Summer season			0.190	0.044 (23%)	0.614	0.047 (8%)	0.081	0.028 (35%)

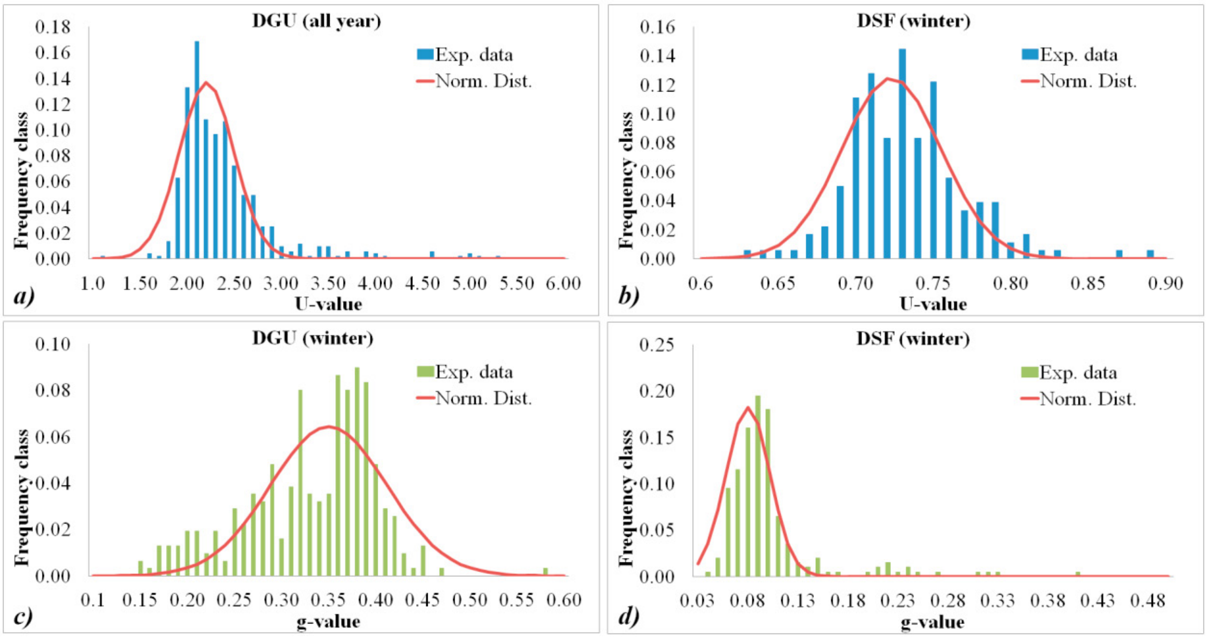

Fig. 1. Experimental data distribution and best-fitting normal function distribution for: *a)* U-value (all year) of the DGU; *b)* U-value (in winter season) of the DSF; *c)* g-value of the DGU (in winter season); *d)* g-value of the DSF (in winter season).

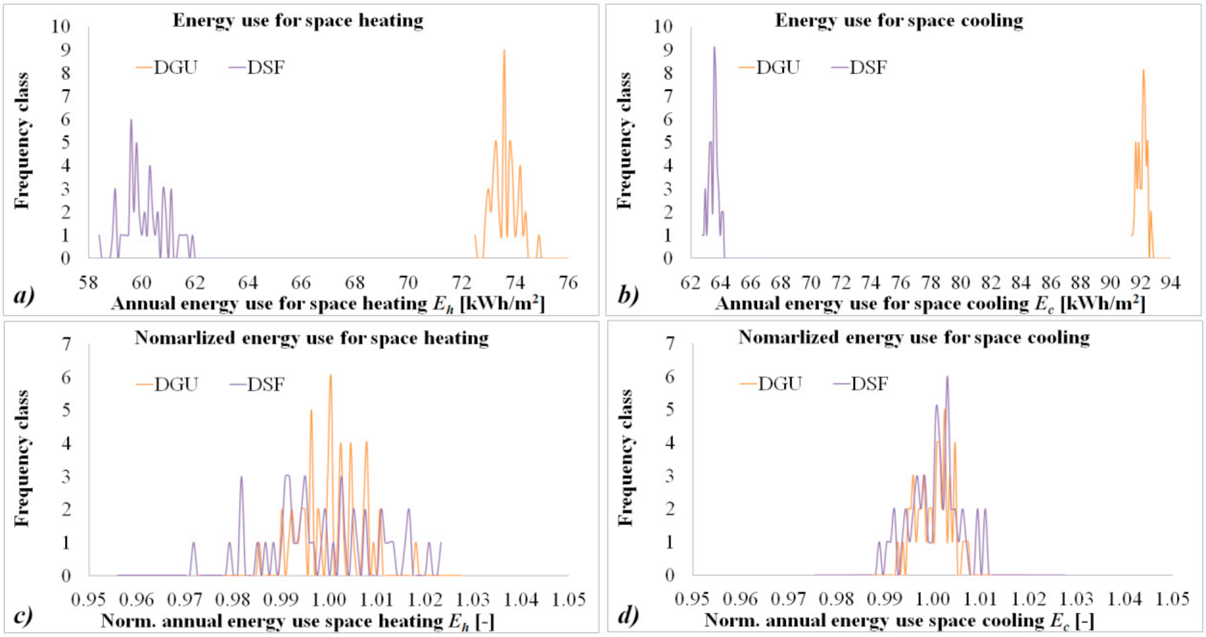

Fig. 2. Numerical data distribution deriving from simulations, for DGU and DSF, for: *a)* annual energy use for space heating; *b)* annual energy use for space cooling; *c)* annual normalized energy use for space heating; *d)* normalized annual energy use for space cooling.

4. Conclusion

Simplified performance metrics such as U-value and g-value are not capable of fully describing the thermophysical behavior of advanced façade systems such as DSF. However, when it comes to the analysis of the impact of these metrics on the energy use for space heating and cooling, especially in the preliminary design phase, their lack of representativeness might not be too significant so that the computed energy demand is far from the "real" one, which could be achieved by means of a more detailed modelling. This circumstance can be related to the fact that advanced façade systems already show a very good performance in terms of energy conservation. Therefore, a relatively small "mistake" in a calculation involving such technologies can still result in a modest or even negligible inaccuracy when energy use is computed for the entire building, where several other elements affect the calculation.

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