Simulative Applications of Novel Indicators for the Characterization and Performance Evaluation of Transparent Facades

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Abstract

Modern glazing systems, including triple-glazing with integrated blinds and advanced façade technologies, exhibit complex thermal behaviors that traditional metrics like the Solar Heat Gain Coefficient (SHGC) and the thermal transmittance (U-value) inadequately capture. This paper introduces novel Key Performance Indicators (KPIs) for assessing the solar performance of glazing units under dynamic, realistic conditions. Such new proposed KPIs — Daily Integrated SHGC and Maximum Solar Gain Ratio MSGR — provide a more accurate reflection of a building's energy performance by considering daily variations in solar exposure and the way the radiation is transferred through a complex transparent component. This research aims to validate the new KPIs in a simulated environment before applying them to actual building components, offering a comprehensive evaluation of their variability with changing environmental and configuration variables.

1. Introduction

1.1 Background

One of the most significant challenges in developed countries is upgrading both new and existing buildings to extremely high efficiency standards, aiming for low-consumption structures (Chel & Kaushik, 2018). Specifically, improving the transparent components of building envelopes allows for natural light penetration, leading to substantial energy savings on lighting. However, these elements also significantly contribute to heating and cooling requirements. In recent years, the evolution of glazing systems for windows and facades has resulted in increased technological complexities, enhancing performance (Favoino et al., 2022). While single and double-pane systems were the standard decades ago, contemporary buildings frequently feature triple-glazing systems, often equipped with integrated blinds, internal curtains, fixed and movable shading. Additionally, the market is seeing a rise in façades with ventilated or closed air cavities due to their protective function and appealing aesthetics (de Gracia et al., 2015). Hence, these contemporary façade systems exhibit heightened thermal inertia and complexity compared to traditional glazing units (Demanega et al., 2023).

The conventional metric used for characterizing the solar gain performance of transparent facade components is the Solar Heat Gain Coefficient (SHGC), also known as the g-value, in the presence of solar radiation and the thermal transmittance (U-value). The SHGC quantifies the ratio between primary – solar transmission - and secondary – absorbed and emitted toward the inner face - energy fluxes entering indoor spaces and the solar radiation incident on the outdoor layer of the glazing system. This indicator is conventionally calculated or measured in two main ways: numerical methods based on spectrophotometric measurements and solar calorimetric methods under steady-state conditions in a controlled environment. Various established numerical techniques exist for calculating a window's g-value (EN 410:2011, ISO 9050:2003, ISO 15099:2003, UNI EN ISO 52022-1). Despite this, the simplifications, and assumptions inherent in these methods, particularly when dealing with complex window systems,

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may lead to underestimated or overestimated outcomes. Conversely, experimental approaches offer researchers a more comprehensive understanding of the underlying heat transfer mechanisms, thus addressing the limitations of numerical methods (Moghaddam et al., 2023).

The conventional measurement of SHGC is performed under steady-state conditions (ISO 19467:2017, NFRC 201–210:2010) and may not accurately reflect the true performance of complex facades. In fact, glazing units are subject to a wide range of solar altitude and azimuth angles, air temperatures, and other weather variables, whereas standard procedures have fixed boundary conditions: i.e., temperatures, wind velocity, irradiance, and orthogonal angle of incidence (ref ISO 19467:2017 and NFRC 201–210:2010), which do not cover the whole environmental conditions that the façades face during their lifetime. Moreover, the complexities of the mentioned façade technologies result in non-uniform and adaptable behaviours to the dynamic outdoor conditions. Nevertheless, during the design phase the conventional SHGC is adopted to estimate the solar heat loads to design the cooling system. Goia & Serra (2018) proposed a methodology for calculating the solar factor and U-value for glazing units under real conditions, developing a set of sensors that can be installed on windows or façade transparent elements. This method accounts for the variability of results according to solar altitude.

This research aims to address the limitations of traditional steady-state calculations for assessing the solar performance of glazing systems. Specifically, it seeks to develop and validate novel Key Performance Indicators (KPIs) that accurately reflect the dynamic environmental conditions affecting glazing units. By introducing the Daily Integrated SHGC and the Maximum Solar Gain Ratio, the study attempts to provide a more comprehensive and realistic evaluation of solar heat gains, considering the variability in solar altitude, azimuth angles, and other climatic factors.

2. Methods

2.1 New KPIs Definition

To overcome the limitation of the current calculation approach of the solar gain, this paper introduces and discusses novel KPIs to characterize the solar performance of glazing units under real and dynamic conditions, along with a comprehensive methodology for their calculation. Specifically, the first proposed indicator is the Daily Integrated SHGC (INT SHGC), representing the integrated value of the SHGC over an entire clear sky day. The second is the Maximum Solar Gain Ratio (MSGR), quantifying the ratio between the daily maximum solar heat gain flux and the daily maximum solar irradiance incident on the outer side of the facade. The first KPI, considered for clear sky days, is calculated as follows:

$$INT\ SHGC = \frac{\int_{i=1}^{N} q_{int_i} + \int_{i=1}^{N} I_{sol,\,int_i}}{\int_{i=1}^{N} I_{sol,ext_i}} \quad [-] \qquad (1)$$

Here, q_{int} represents the secondary flux, $I_{sol,int}$ is the solar shortwave irradiance entering the indoor environment, and $I_{sol,ext}$ is the solar irradiance hitting the outer face of the window. Within this approach, the dynamics of the façade systems and of the solar movement are crucial for the overall results, differently from a steady-state calculation as the one standard SHGC. With this approach, the daily overall performance is considered, without focusing on just one setting.

Additionally, MSGR, is defined as:

$$\text{MSGR} = \frac{(q_{int}+I_{sol,int})_{max}}{I_{sol,ext_{max}}} \quad [-] \qquad (2)$$

The MSGR quantifies the ratio between the maximum amount of power entering the indoor environment through the glazing throughout the day and the maximum solar irradiance hitting the external side of the glazing. Knowing the peak irradiance hitting on the outer surface on a certain day, this metric aids in estimating the peak solar gain that the cooling system must compensate. The offset of these two peaks can be calculated, to determine time delay from one to the other.

2.2 Numerical Evaluation

To perform the analysis, a TRNSYS model was built integrating different components. TRNSYS solves equations for dynamic simulations using a modular approach, integrating numerical solvers for differential and algebraic equations, and iterating between modules to ensure convergence of solutions. An existing model simulating the behavior and performance of a window with a ventilated cavity (Demanega et al., 2022) was adopted. Such a model is composed of a Type56 for the building (with its window) and a Type169 to simulate the airflow in the cavity according to ISO 15099. In this model, the window is installed in a shoebox building without any other windows. All the simulations were performed using timesteps of 10 minutes.

The glazing configuration was represented, in terms of the optical and thermal model, using a BSDF (Bidirectional Scattering Distribution Function) data file generated with WINDOW software v. 7.8 (Software Tools | Windows & Daylighting (lbl.gov)). The window (1 m x 1.34 m in dimension) consists of a low emissivity double-glazed internal unit with two panes separated by a layer of Argon (95 %) and air (5 %), along with a ventilated cavity where Venetian blinds are installed. The cavity is enclosed by an external single glass pane. In this simulation campaign, the Venetian blinds are constantly kept deployed at 0°. WINDOW not only produced a BSDF data file, but also calculated the SHGC and other KPIs according to the numerical standard approaches. The most important KPIs are reported in Table 1.

Table 1 – Significant KPIs of the window calculated according to ISO 15099 in WINDOW 7.8

SHGC	61.2 %
U factor	2.159 W/(m² K)
$\mathbf{T_{sol}}$	45.8 %
$\mathbf{T_{vis}}$	56.2 %

2.3 Parametric Simulations

To investigate the variability of the proposed KPIs according to the external conditions, simulations and KPIs calculations have been performed for a set of variables. These variables included the location, the season, and the façade orientation.

The locations chosen for this study are Athens (Greece), Bolzano (Italy) and Oslo (Norway). These are located at different latitudes and climatic zones. The weather files for the locations under study were obtained using METEONORM software (Meteonorm Version 8 - Meteonorm (en)), which provided the respective Typical Meteorological Years. The orientations of the façade have been defined exactly as the four cardinal points (Azimuth: 0°, -90°, 90°, 180°). The analysis covered all four seasons, each evaluated within a specific timeframe centered around the solstice or equinox day marking the beginning of the season. The evaluation period extended from 7 days before to 7 days after this reference day. For each of these periods, only the two days with the highest solar radiation levels, considered as clear sky days, have been taken into consideration, and the results of these two days have been averaged.

The variables involved in the series of simulations are reported in Table 2.

Table 2 – Variables involved in the simulation campaign

Location	Season	Orientation
Bolzano	Spring	South
Oslo	Summer	East
Athens	Autumn	West
	Winter	North

3. Results and Discussion

Table 3 presents the "INT SHGC" and "MSGR" values for the four cardinal directions (South, North, East, West) in three different locations (Bolzano, Oslo, and Athens) across the four seasons (Spring, Summer, Autumn, Winter).

The results highlight that, in general, the KPIs are lower than the standard SHCG (61.2 %). This indicates the calculated performance based on ideal steady-state conditions tends to overestimate the SHGC compared to real-world dynamic conditions.

Table 3 – Results for the novel KPIs calculation

		Spring		Summer		Autumn		Winter	
		INT SHGC	MSGR	INT SHGC	MSGR	INT SHGC	MSGR	INT SHGC	MSGR
South	Bolzano	33.2%	33.9%	30.2%	30.0%	32.4%	33.7%	49.2%	48.5%
	Oslo	40.6%	42.0%	30.3%	31.6%	37.7%	39.9%	55.5%	56.5%
	Athens	30.8%	32.3%	35.3%	33.1%	29.6%	31.2%	41.6%	39.2%
North	Bolzano	39.4%	39.4%	36.3%	34.3%	39.5%	39.5%	39.2%	39.2%
	Oslo	39.0%	38.9%	37.6%	40.4%	39.3%	39.4%	39.3%	39.3%
	Athens	39.6%	39.6%	36.6%	35.5%	39.7%	39.7%	39.4%	39.3%
East	Bolzano	39.6%	50.7%	38.6%	46.4%	39.5%	47.2%	40.1%	49.2%
	Oslo	41.6%	52.9%	40.2%	51.8%	42.4%	53.5%	34.8%	35.2%
	Athens	39.6%	51.8%	38.1%	41.6%	39.0%	50.2%	38.8%	49.7%
West	Bolzano	40.0%	48.1%	39.2%	43.2%	40.8%	50.1%	39.1%	50.3%
	Oslo	42.1%	49.9%	40.3%	44.9%	43.0%	53.8%	32.8%	34.2%
	Athens	38.7%	51.4%	38.9%	43.0%	39.5%	53.8%	38.9%	52.1%

Table 4 – Difference between calculated novel KPIs and SHGC calculated with WINDOW (61.2 %)

		Spring		Summer		Autumn		Winter	
		INT SHGC	MSGR	INT SHGC	MSGR	INT SHGC	MSGR	INT SHGC	MSGR
South	Bolzano	-28.1%	-27.4%	-31.1%	-31.2%	-28.9%	-27.5%	-12.1%	-12.7%
	Oslo	-20.6%	-19.2%	-31.0%	-29.7%	-23.6%	-21.4%	-5.8%	-4.7%
	Athens	-30.5%	-28.9%	-25.9%	-28.1%	-31.6%	-30.1%	-19.6%	-22.0%
North	Bolzano	-21.9%	-21.8%	-25.0%	-26.9%	-21.8%	-21.7%	-22.0%	-22.0%
	Oslo	-22.3%	-22.4%	-23.6%	-20.8%	-21.9%	-21.9%	-21.9%	-21.9%
	Athens	-21.6%	-21.6%	-24.6%	-25.8%	-21.6%	-21.5%	-21.9%	-21.9%
East	Bolzano	-21.7%	-10.6%	-22.6%	-14.9%	-21.7%	-14.1%	-21.1%	-12.1%
	Oslo	-19.6%	-8.4%	-21.0%	-9.4%	-18.9%	-7.7%	-26.4%	-26.0%
	Athenes	-21.6%	-9.4%	-23.2%	-19.7%	-22.3%	-11.1%	-22.5%	-11.6%
West	Bolzano	-21.2%	-13.2%	-22.0%	-18.0%	-20.5%	-11.2%	-22.1%	-11.0%
	Oslo	-19.1%	-11.4%	-20.9%	-16.3%	-18.3%	-7.4%	-28.5%	-27.0%
	Athens	-22.5%	-9.8%	-22.3%	-18.3%	-21.8%	-7.4%	-22.4%	-9.1%

The calculated KPIs exhibit significant variability based on the location, orientation, and season, underscoring the importance of considering these factors in the design and evaluation of building envelopes. This discrepancy is particularly pronounced during the summer months in Bolzano and Athens, where the Daily Integrated SHGC drops by approximately 31.1 % and 25.9 %, respectively. This significant difference is due to the high solar elevation in this season, which cause higher angles of incidence on the façade throughout the days. This reduction highlights the impact of dynamic environmental conditions, which are not accounted for in standard steady-state calculations.

3.1 Location Analysis

In Table 3, it is possible to observe how the calculated KPIs vary according to the location, keeping the same orientation and same season. Generally speaking, the variability of the KPIs based on location is higher for the southern orientation, due to the significant range of solar elevation across different latitudes. For instance, the differences in KPIs during spring for the south orientation are illustrated in Figure 1. In this case, Oslo, with a higher latitude, exhibits the highest values, while Athens, with a lower latitude, shows the lowest values. The range of values is close to 10 %.

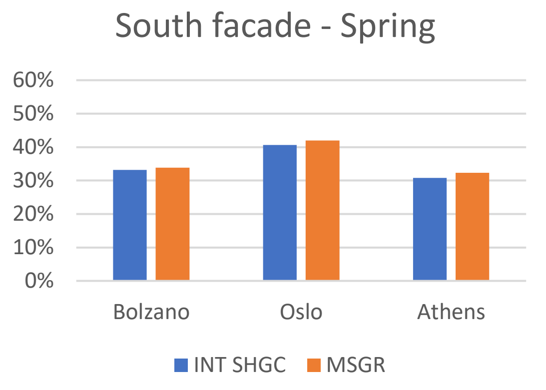

Fig. 1 – KPIs values for South facade – Spring

In Figure 2, the trends of the energy fluxes through the window are illustrated for two days in spring in Oslo and Athens, for south-oriented façade. While the contribution of the secondary flux is similar (around 20 % compared to external incident radiation), in Oslo there is a higher contribution of the directly transmitted radiation, because of a lower solar elevation. This causes the increase in the KPIs values.

For other combinations of season and orientation, such as Winter-South façade, the range of results is even higher than the previously illustrated combination, while in many other cases the range is significantly lower, indicating a smaller impact of the location.

3.2 Seasonal Analysis

From another point of view, it is possible to appreciate the differences in results according to the season in which the simulations are run. Also in this case, the solar elevation and the incidence angle on the façade are subject to high variability throughout the year. One interesting situation to analyse is the combination Oslo-South orientation. In Figure 3, the overall KPIs results are represented. In this chart, the large difference between summer and winter is quite noticeable. Also in this case, the influence of the sun path is crucial.

The trend of energy fluxes for one day of winter and one day of summer are illustrated in Figure 4. Because of a lower solar angle, the transmitted solar radiation amount, with respect to the incident solar radiation, is significantly higher in winter, causing high values of the KPIs.

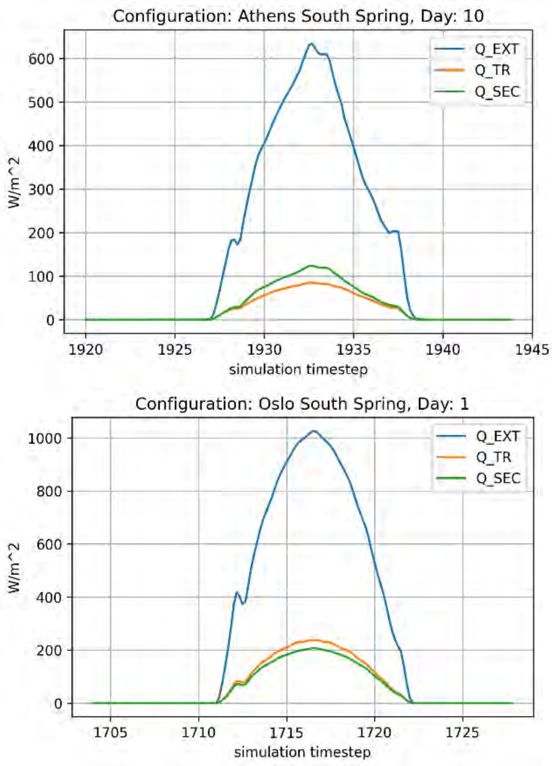

Fig. 2 – Energy fluxes trends for the locations of Athens and Oslo

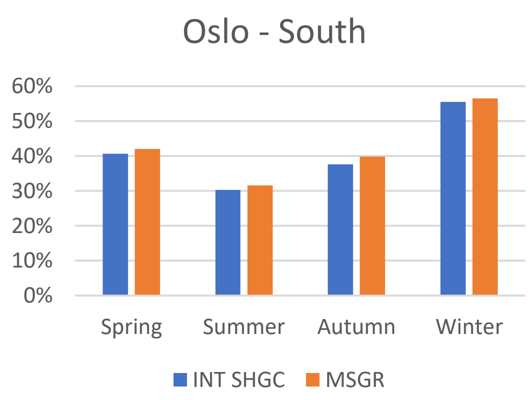

Fig. 3 – KPIs values for Oslo – South

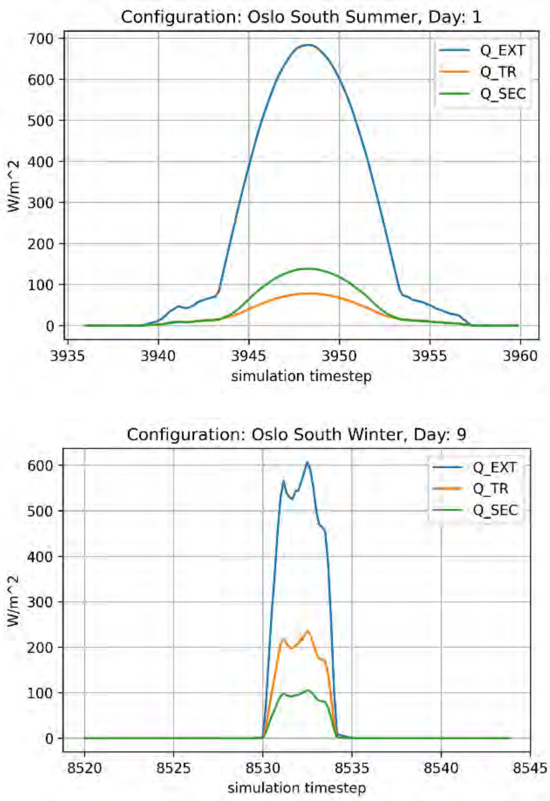

Fig. 4 – Energy fluxes trends for Winter and Summer in Oslo

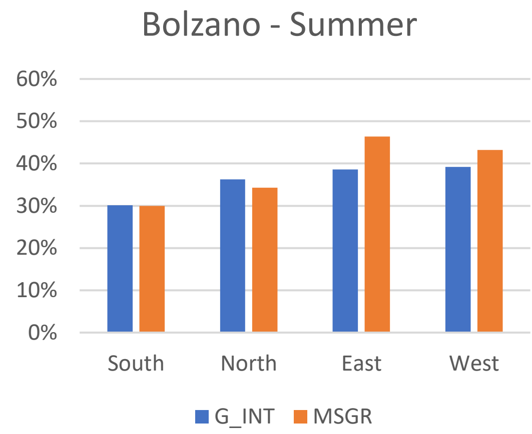

Fig. 5 – KPIs values for Bolzano – Summer

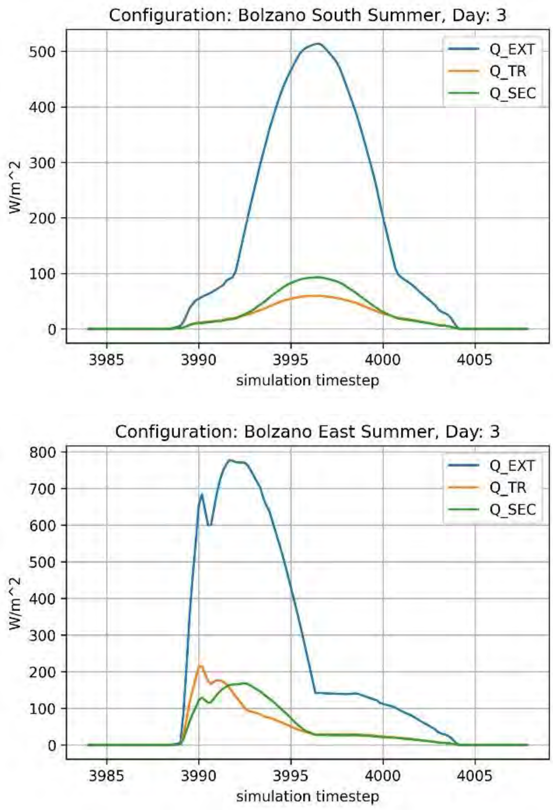

Fig. 6 – Energy fluxes trends for South and East orientation in Bolzano

3.3 Orientation Analysis

Furthermore, the orientation of the façade has an influence on KPIs simulated results. From Table 3 and Table 4 it is possible to clearly see how South orientation presents lower values of the KPIs. On the other hand, West and East orientations show higher values. As an example, in Figure 5, there is a representation of the results for the location of Bolzano in the summer season.

To understand the reasons behind these results, also in this case the trends of the energy fluxes can be analyzed. In the morning (or in the afternoon for the west orientation), the sun is low and frontal to the façade, increasing the amount of transmitted solar radiation. The performance is different for the south orientation, as the sun hits the façade at different angles of incidence throughout the day. Within this comparison, it is evident that, in the east configuration, the peak of energy flux passing through the window is happening much earlier than the peak of solar radiation hitting the external side. In fact, while for this configuration the offset between the peaks is of approximately 90 minutes, for south configuration the two peaks are simultaneous.

3.4 Overall Discussion

The variability observed in the calculated KPIs underscores the complex interplay between environmental conditions and the performance of glazing systems. This variability highlights the necessity of considering dynamic factors such as location, season, and facade orientation when evaluating and designing energy-efficient building envelopes. It becomes evident that traditional steady-state calculations are insufficient for capturing the true performance of these systems, tending to overestimate the solar gain, which can lead to incorrect choice in the design of the building envelope and HVAC system. The significant differences (up to 31 %) between the KPIs and the standard SHGC values emphasize the need for a more nuanced approach that accounts for real-world conditions. By doing so, we can achieve a more accurate prediction of solar heat gains, leading to better-informed and conscious design and ultimately contributing to more sustainable and energy-efficient buildings.

4. Conclusions

The evolution of glazing systems for windows and facades has significantly contributed to the energy efficiency of buildings. This paper introduces novel Key Performance Indicators (KPIs) to better characterize the solar performance of glazing units under real and dynamic conditions, offering a more comprehensive understanding of their actual performance compared to traditional steady-state metrics. The research utilized a TRNSYS model to simulate the behaviour of a window with integrated Venetian blinds in fixed horizontal position, calculating the proposed KPIs. Results across different locations, orientations, and seasons were analysed. The findings highlight several key points. Firstly, the Daily Integrated Solar Heat Gain Coefficient and Maximum Solar Gain Ratio show considerable variability based on location, season, and orientation. This underscores the importance of considering these dynamic factors in the design and evaluation of building envelopes. The actual performance of façade systems cannot be accurately captured by steady-state calculations alone.

Secondly, the results demonstrate that the performance of glazing systems calculated in dynamic and more realistic conditions is often different than what is predicted by standard steady-state SHGC values. This discrepancy is especially pronounced during the summer months and in locations with high solar elevation, where the dynamic conditions lead to lower actual solar heat gain compared to steady-state predictions.

Lastly, the proposed KPIs, Daily Integrated SHGC and Maximum Solar Gain Ratio, provide a more realistic measure of glazing performance under dynamic conditions. They account for the variability of solar altitude, azimuth angles, and other environmental factors, offering a better prediction of solar heat gains and thus aiding in the accurate design and evaluation of cooling systems.

Current limitations of the model are related to the possibility to consider thermal inertia of the window, which is currently not included in the calculation method. Influencing mainly the MSGR indicator calculation, which also considers the time-delay of the solar energy peak respect to the incident radiation. In this sense, further developments may involve the improvement of the TRNSYS model to better represent the real performance of the glazing system.

Future research should also focus on experimenting and validating these KPIs with experimental data and extending the analysis to other types of glazing systems and façade configurations. Additionally, the development and integration of advanced sensors and data collection methods in real buildings will further enhance the accuracy and applicability of these KPIs in practical settings. By incorporating real environmental conditions into the evaluation process, architects, engineers, and designers can make more informed decisions, ultimately leading to buildings that are better adapted to their specific climatic and operational contexts.

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