

# A Comparative Study on Building Energy Performance According to Window Form in Pyongyang Climate: Focusing on Protruded, Polygonal, and Curved Windows

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**Abstract-** Window design is a critical factor significantly influencing building aesthetics, daylighting performance, visual comfort, and energy consumption. Conventional energy-saving strategies often rely on reducing window area, which negatively impacts architectural aesthetics and user satisfaction. This study proposes a novel form-oriented design approach that enhances energy efficiency while maintaining the window area. Four window geometries—flat, polygonal, protruded, and curved—were compared under identical area and material conditions. Key performance indicators included U-value, Solar Heat Gain Coefficient (SHGC), cooling and heating loads, and daylighting performance. The analysis revealed that curved windows achieved the highest cooling performance with an 18.2% reduction in cooling load but exhibited a significant drawback with an 8.2% increase in heating load, indicating substantial winter heat loss. Protruded windows showed a minimal cooling load reduction of only 0.3% and a 3.6% increase in heating load. Polygonal windows demonstrated the most balanced performance, with a 7.1% reduction in cooling load and a 3.8% increase in heating load. These results suggest that in a cold climate like Pyongyang, winter heating performance has a greater impact on annual energy consumption than summer cooling performance, implying that window form selection should not be based solely on summer performance.

**Keywords –** Green building, energy saving, window design, form-oriented design, fixed window area, comparative analysis.

## I. INTRODUCTION

In contemporary urban architecture, the formal value of facades has become a core design element. Windows are crucial components that determine a building's formal characteristics as well as user satisfaction regarding daylighting, ventilation, and views. With technological advancements and the diversification of window types, the visual and formal value of windows is increasingly emphasized. However, energy consumption issues caused by heat loss and excessive solar radiation ingress through windows persist. It is known that over 30% of total building energy loss occurs through windows, prompting various studies aimed at improvement.

Existing research on energy-efficient windows has primarily focused on reducing window area or applying high-performance glazing and insulation materials. However, indiscriminately reducing window area limits daylighting and views, hindering facade composition. Furthermore, the high cost of high-performance glazing limits its widespread application. To address these issues, recent attempts to improve energy performance through form and design optimization while maintaining window area are increasing.

[1] demonstrated that optimizing geometric window parameters—such as window height (WH) and sill height (SH)—beyond the conventional window-to-wall ratio (WWR) can significantly reduce heating, cooling, and lighting energy consumption in high-rise buildings. [3] showed that a curved BIPV window with a central angle of 120°, under the same window area, ensures uniformity of solar heat absorption and reduces energy consumption. [15] conducted a comparative analysis of energy performance and life cycle assessment of various window systems. [16] quantitatively analyzed the impact of window design on building energy consumption and user satisfaction under various European climatic conditions.

Recent research trends on BIPV windows and shading are comprehensively presented in the review by [4] and a critical review of window design methodologies for high-performance buildings was conducted by [11]. [5] quantitatively analyzed the impact of window retrofitting strategies (double/triple glazing, vacuum glazing, Low-E coating) on energy consumption in residential buildings under the temperate climate of the UK. [2] quantitatively analyzed the impact of window parameters (area, U-value) on energy demand and CO<sub>2</sub> emissions under various European climate conditions. The sensitivity analysis results of [9] quantitatively support the

importance of window-related variables and indirectly validate the appropriateness of the form variable settings in this study. [14] demonstrated that 3D tessellation curtain wall facades could simultaneously improve visual comfort and energy production, providing a theoretical background for the polygonal window design in this study.

While these previous studies indicate that window form significantly impacts energy performance and offer potential for energy savings without area reduction, they largely remain focused on analyzing individual relationships between form and performance. Furthermore, existing research has primarily concentrated on temperate climates or cooling-dominant regions, leaving the applicability in a cold, dry climate like Pyongyang (Dwa) insufficiently examined.

Therefore, this study aims to quantitatively compare and analyze the seasonal energy performance (cooling load, heating load, lighting energy) of protruded, polygonal, and curved windows while maintaining window area under the climatic conditions of Pyongyang, and to propose an optimal design direction for window forms based on climatic conditions. Unlike previous studies that primarily focused on WWR optimization or were limited to specific forms (e.g., curved windows), this study distinguishes itself by comprehensively comparing four window geometries—flat, polygonal, protruded, and curved—under identical window area conditions. Furthermore, while existing research mainly focused on the relationship between building form and energy performance, this study proposes a new design approach that integrates energy performance with architectural formal value.

## II. RESEARCH METHOD

This study employed form-oriented design and simulation analysis methods to investigate changes in energy performance according to formal design variables under fixed window area conditions.

### Literature Review

Through a review of previous literature, trends in existing window energy research were identified, and limitations of area reduction approaches were derived. Recent form-oriented energy efficiency strategies were examined and utilized as foundational data. The multi-parameter optimization approach of this study refers to the methodology applied by [6] to residential building window design in a hot-arid climate. The machine learning-based performance prediction framework proposed by [7] shares methodological similarities with the integrated simulation approach of this study, and the research by [8] used the same Ladybug Tools-based simulation framework as this study. The starting point of this study was to identify the limitations of conventional window energy strategies. The literature review confirmed that previous studies primarily reduced building energy consumption by adjusting

WWR or utilizing high-performance glazing. However, it was confirmed that these methods negatively impact building aesthetics and fail to satisfy user needs. Consequently, recent research trends focusing on reducing energy consumption while maintaining window area were identified, establishing the fundamental direction of this study.

### Research Subjects and Form Variable Settings

Based on the premise of identical window area, formal variables were established, and four representative window types were categorized:

Flat Window (Base Case)

Polygonal Window (Polygon)

Protruded Window (Window protruding 300mm outward from the wall)

Curved Window (Curved form with a central angle of  $120^\circ$ )

Figure 1 shows the window forms corresponding to each type.

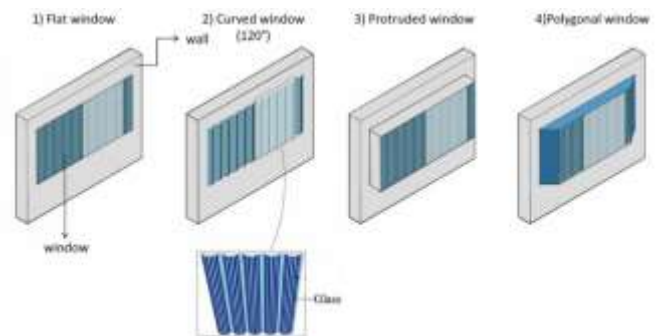


Fig. 1. Various window geometries.

The polygonal window applies the effect of geometric variable (WH, SH) optimization, demonstrated in the study by [1] to a polygonal form. In the multi-objective optimization study for school buildings conducted by [12], WWR and SHGC were also found to be the most important variables. The protruded window integrates the cooling load reduction effect of external shading devices, reported by [15], into the window itself. The curved window adopts the optimal curvature ( $120^\circ$ ) suggested by [3] to simultaneously improve energy and daylight performance. Due to its protruding central portion, the polygonal window absorbs more sunlight than a flat window, potentially saving heating energy during winter. The protruded window was selected because its self-shading effect significantly impacts cooling load reduction. All models applied identical area, identical glazing performance (U-Value  $1.8 \text{ W/m}^2\cdot\text{K}$ , SHGC 0.6), and identical room conditions ( $3.0\text{m (W)} \times 3.9\text{m (L)} \times 2.7\text{m (H)}$ ) to ensure reliable comparison.

### Integrated Simulation

This study selected an integrated simulation method to evaluate building performance during the early design stage. A simulation framework based on the Ladybug Tools Honeybee program within the Grasshopper environment was established to quantitatively analyze energy performance, daylight

performance, thermal performance, and form-specific energy reduction rates. The simulations were performed on an 11th Gen Intel(R) Core(TM) i7-11800H computer (16 CPUs, 16384MB RAM, NVIDIA GeForce RTX 3060 Laptop GPU). Figure 2 intuitively shows the simulation procedure.

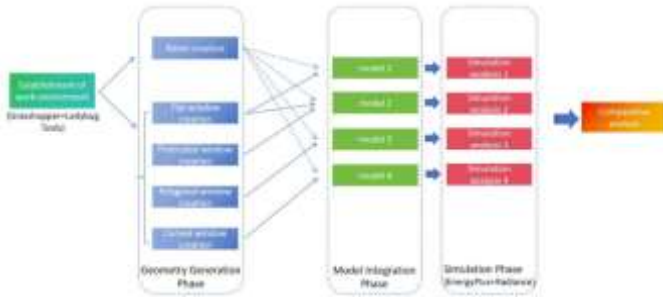


Fig. 2. Flowchart of the research methodology.

Dynamic thermal load analysis of the building was conducted using "EnergyPlus," and daylight performance evaluation was performed based on "Radiance." Standard climate data (EPW) for Pyongyang, Democratic People's Republic of Korea, provided by Grasshopper (PRK\_Pyongyang.470580\_IWEC.epw), was used to reflect actual building environment conditions. A room unit measuring 3.0m (W) × 3.9m (L) × 2.7m (H) was created in Grasshopper, and simulations were conducted to analyze changes in energy consumption, daylight performance, and thermal characteristics when installing different types of windows. Table 1 shows the basic values and data used in the simulations of this study.

Table 1. Basic values used in simulations

Parameter	Value	Unit
Location	Pyongyang, DPRK	-
Climate Zone	Dwa (Cold, Dry Winter)	-
Room Dimensions	3.0 (W) × 3.9 (L) × 2.7 (H)	m
Floor Area	11.7	m <sup>2</sup>
Window Area	2.25	m <sup>2</sup>
Window-to-Wall Ratio (WWR)	Fixed	%
Window U-Value	1.8	W/m <sup>2</sup> ·K
Window SHGC	0.6	-
Weather Data Source	EPW (PRK_Pyongyang.470580_IWEC.epw)	-

### Geometric Modeling and Boundary Conditions

The study's target space was a single zone with dimensions of 3.0m (width) × 3.9m (depth) × 2.7m (height), created using Grasshopper's Box 2PT component. The generated closed polysurface was converted into a Honeybee Room object using

the HB Room from Solid component, with the `_roof_angle_` input set to 60° to distinguish between horizontal surfaces (floor/roof) and vertical surfaces (walls). All walls and windows were assigned identical material properties to ensure a fair comparison in subsequent simulations. Walls were defined as exterior walls. Windows for each geometry were created using the HB Aperture component and then assigned to the corresponding Room's apertures input within the HB Model component. For the protruded window type, the window face was extracted and extruded by 300mm in the normal direction using the Extrude component. The resulting extrusion was then converted into a shading device using the HB Shade component and added to the shades input of the HB Model, thereby modeling it as an integral part of the building envelope.

### Energy Performance Simulation Settings

Dynamic thermal performance analysis of the building was conducted using the EnergyPlus 23.2 engine, developed by the U.S. Department of Energy (DOE). The simulation timestep was set to 4 times per hour (i.e., 15-minute intervals) to balance analysis precision and computational time. Heating and cooling systems were modeled as ideal loads air systems to purely calculate the energy required to maintain zone setpoint temperatures, independent of specific HVAC equipment characteristics. The heating setpoint was defined as 20°C for winter, and the cooling setpoint as 26°C for summer. To isolate the pure performance of the building envelope and exclude internal heat gains (from occupants, lighting, equipment), the occupancy schedule was assumed to be continuously occupied (24/7) throughout the study period. The simulation results calculated included hourly zone cooling load (Zone Ideal Loads Supply Air Total Cooling Energy), zone heating load (Zone Ideal Loads Supply Air Total Heating Energy), and zone lighting electricity consumption (Lights Electricity Energy). These outputs were requested by inputting the exact variable names into an HB Custom Simulation Output component.

### Daylight Performance Simulation Settings

Indoor daylight performance was evaluated using the high-precision ray-tracing engine, Radiance. For the analysis, a sensor grid with a 0.5m × 0.5m spacing was generated at the workplane height (0.75m above the floor) using the HB Sensor Grid from Rooms component. This grid was then assigned to the model via HB Assign Grids and Views. Annual daylight simulations were executed using the HB Annual Daylight recipe, with default Radiance parameters (-ab 2 -ad 5000 -lw 2e-05). No specific occupancy schedule was assigned for daylight analysis, thus applying the default schedule assuming occupancy from 08:00 to 18:00 daily throughout the year. Key performance metrics calculated included Useful Daylight Illuminance (UDI, 100-2000 lux), Spatial Daylight Autonomy (sDA, percentage of floor area receiving at least 300 lux for 50% of occupied hours), and Annual Sunlight Exposure (ASE, percentage of floor area receiving more than 1000 lux for 250 occupied hours per year). These metrics were referenced

against the evaluation criteria of the EN 17037 and IES LM-83 standards, respectively.

**Data Collection and Post-Processing**

All simulation result data were imported back into the Grasshopper environment using HB Read Custom Result and HB Read Annual Results components. The collected hourly data was exported to text files (.csv) for statistical analysis using spreadsheet software (e.g., Excel). Monthly energy consumption patterns and the distribution of daylight performance metrics were visualized using LB Monthly Chart and LB Spatial Heatmap components. Performance comparisons among the four window geometries were intuitively analyzed by overlaying the respective datasets on the same graphs.

**Formal Value and Comprehensive Evaluation**

Based on the energy and daylight performance analysis results, the practical value of each window form was comprehensively evaluated. Formal value was assessed focusing on facade aesthetics, three-dimensionality, and formal completeness, linking these with energy performance to derive an optimized form-oriented design strategy from a comprehensive perspective.

**III. RESEARCH RESULTS**

Even under identical window area conditions, energy performance clearly differed according to window form. Compared to the baseline flat window model, all other forms showed reduced or similar cooling loads, but most showed increased heating loads. Table 2 presents the annual energy performance comparison results for the four window types.

Table 2. Annual energy performance comparison by form

	Flat (Base Case)	Polygonal	Protruded	Curved (120°)
Cooling Load (kWh/m <sup>2</sup> /yr)	26.68	24.78	26.6	21.82
Heating Load (kWh/m <sup>2</sup> /yr)	170	176.4	176.2	184
Lighting Energy (kWh/m <sup>2</sup> /yr)	27.2	26.8	26.5	26.2
Cooling Reduction (%)	-	7.1	0.3	18.2

Heating Reduction (%)	-	-3.8	-3.6	-8.2
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**Cooling Load**

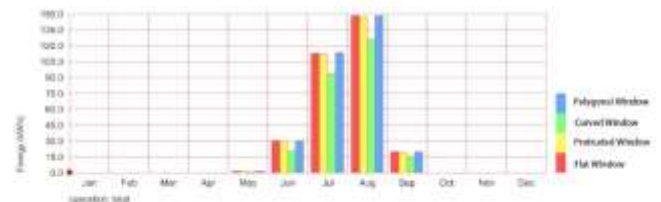


Fig. 3. Annual cooling load diagram

Figure 3 shows a chart of the annual cooling load according to window form. Analysis of cooling load revealed that the curved window achieved the highest reduction of 18.2% compared to the flat window, recording 21.82 kWh/m<sup>2</sup>/yr. This is analyzed to be because the concave form of the curved window effectively blocks direct solar radiation during summer afternoons when the sun altitude is high, simultaneously dispersing light and reducing the cooling load. The polygonal window also showed a 7.1% reduction effect with 24.78 kWh/m<sup>2</sup>/yr, but the protruded window exhibited only a minimal 0.3% reduction effect with 26.60 kWh/m<sup>2</sup>/yr, indicating virtually no improvement in cooling performance.

**Heating Load**

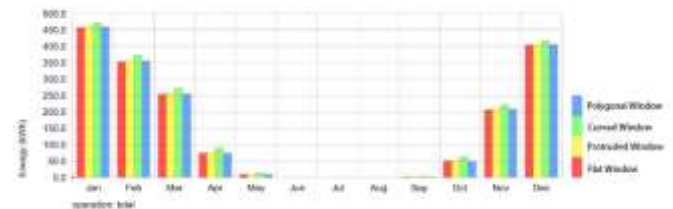


Fig. 4. Annual heating load diagram.

Figure 4 shows a chart of the annual heating load according to window form. As shown in Figure 4, all alternative window forms recorded higher heating loads than the flat window (170.0 kWh/m<sup>2</sup>/yr). The curved window showed the largest increase of 8.2%, reaching 184.0 kWh/m<sup>2</sup>/yr. This is judged to be because the curved form, given the low winter sun altitude (approx. 27° at the winter solstice in Pyongyang), rather hinders solar heat gain. The polygonal and protruded windows showed increases of 3.8% (176.4 kWh/m<sup>2</sup>/yr) and 3.6% (176.2 kWh/m<sup>2</sup>/yr), respectively, demonstrating relatively less degradation in heating performance compared to the curved window. The thermal performance characteristics of the protruded window can be explained by a mechanism similar to

the internal geometry optimization results of energy-efficient windows reported by [10].

### Lighting Energy

Analysis of lighting energy showed that all alternative window forms achieved slight reductions compared to the flat window (27.2 kWh/m<sup>2</sup>/yr). The curved and protruded windows exhibited the best daylight performance with reductions of 3.7% (26.2 kWh/m<sup>2</sup>/yr) and 2.6% (26.5 kWh/m<sup>2</sup>/yr), respectively. The polygonal window also showed a reduction of 1.5% (26.8 kWh/m<sup>2</sup>/yr). This is attributed to the optical properties of these forms, which guide or disperse light deeper into the interior. However, as the absolute differences were not large, the superiority between forms regarding lighting energy was not pronounced.

### Daylight Performance Analysis

UDI (Useful Daylight Illuminance), sDA (Spatial Daylight Autonomy), and ASE (Annual Sunlight Exposure) were analyzed through annual daylight simulations. Table 3 shows the daylight performance indicators for each form

Table 3. Annual daylight performance comparison by form

Window Type	UDI (%)	sDA (%)	ASE (%)
Flat	68	65	22
Polygonal	72	70	18
Protruded	70	68	12
Curved (120°)	75	73	16

The analysis showed that the curved window exhibited the best daylight performance with UDI 75% and sDA 73%, due to its optical properties dispersing light uniformly within the room. The protruded window recorded the lowest ASE value of 12%, indicating the least glare risk due to its self-shading effect. The polygonal window showed overall good daylight performance with UDI 72%, sDA 70%, and ASE 18%.

### Comprehensive Analysis and Interpretation

Synthesizing the energy and daylight performance reveals distinct advantages and disadvantages for each form.

The curved window showed the best results in cooling load reduction (18.2%) and daylight performance (UDI 75%, sDA 73%), but winter energy performance was significantly degraded due to an 8.2% increase in heating load. This could be a critical drawback in a climate like Pyongyang (Dwa), which has long and cold winters.

The polygonal window demonstrated the most balanced performance, with a 7.1% reduction in cooling load, a 3.8% increase in heating load, and good daylight performance (UDI 72%, sDA 70%). The increase in heating load was half that of the curved window, making it the most realistic alternative in terms of annual energy performance.

The protruded window had a minimal cooling load reduction effect of 0.3%, but its heating load increase rate was also relatively low at 3.6%, and it had the lowest ASE value of 12%, minimizing glare risk. Its daylight performance (UDI 70%, sDA 68%) was also acceptable.

These results provide the important implication that, under the climatic conditions of Pyongyang, winter heating performance has a greater impact on annual energy consumption than summer cooling performance. Therefore, even if a window form offers excellent cooling performance, it may not be suitable for the Pyongyang climate if it significantly degrades heating performance. In this study, the polygonal window is judged to be the most suitable form for the Pyongyang area due to its best balance between cooling and heating performance.

### Discussion

The cooling load reduction effect of the curved window in this study (18.2%) partially aligns with the results of the Chinese study by [3], but the magnitude of the heating load increase (8.2%) was larger than expected. This difference stems from the specificity of the Pyongyang (Dwa) climate. Pyongyang has long winters and low solar altitude (approx. 27° at the winter solstice), where the optical properties of the curved window (central angle 120°) might actually hinder solar heat gain. This suggests that the performance of the same window form can vary significantly depending on climatic conditions.

The protruded window showed a minimal cooling load reduction of 0.3%, indicating that the cooling load reduction effect of shading devices reported by [15] may be limited in cold climates. Its heating load increase (3.6%) was also relatively small. The polygonal window, with a 7.1% cooling load reduction and a 3.8% heating load increase, showed the most balanced performance and is evaluated as the most stable option for the Pyongyang climate.

In summary, in the Pyongyang climate, winter heating performance has a greater impact on annual energy consumption than summer cooling performance. Therefore, a strategic approach tailored to the building's purpose and energy goals is necessary, rather than selecting window forms based solely on cooling load reduction.

## IV. CONCLUSION

This study quantitatively compared and analyzed the impact of four window forms (flat, polygonal, protruded, curved) on the energy performance of an office building under the fixed window area condition in the Pyongyang (Dwa) climate. Integrated simulations based on EnergyPlus and Radiance engines were used to evaluate cooling load, heating load, lighting energy, and daylight performance (UDI, sDA, ASE), leading to the following main conclusions.

### Summary of Main Findings

First, in terms of cooling load, the curved window showed the highest reduction of 18.2% compared to the flat window, demonstrating the best summer cooling performance. The polygonal window also showed a reduction of 7.1%, but the protruded window exhibited a minimal effect of only 0.3%, showing almost no improvement in cooling performance.

Second, in terms of heating load, all alternative window forms recorded higher loads than the flat window. The curved window showed the largest increase of 8.2%, indicating significant winter heat loss. The polygonal and protruded windows showed relatively less degradation in heating performance, with increases of 3.8% and 3.6%, respectively.

Third, in terms of lighting energy, all forms achieved slight reductions compared to the flat window. The curved and protruded windows showed the best daylight performance with reductions of 3.7% and 2.6%, respectively, while the polygonal window also showed a reduction of 1.5%.

Fourth, in terms of daylight performance, the curved window provided the best daylight environment with UDI 75% and sDA 73%. The protruded window had the lowest ASE of 12%, indicating the least glare risk. The polygonal window showed balanced performance across all indicators.

### Comprehensive Form Evaluation and Practical Implications

The polygonal window demonstrated the most balanced results with a 7.1% reduction in cooling load, a 3.8% increase in heating load, and a 1.5% reduction in lighting energy. Its daylight performance (UDI 72%, sDA 70%) was also good, making it the most universally applicable form for the Pyongyang climate. Notably, its heating load increase was half that of the curved window, and in a cold climate where winter heating load dominates, such balance can be an important design criterion.

The protruded window has a minimal cooling load reduction effect of 0.3%, making it difficult to expect cooling performance improvement in the Pyongyang climate. However, its heating load increase rate is relatively low at 3.6%, and its ASE value of 12% is the lowest, minimizing glare risk. Therefore, it can be used selectively in spaces where daylight environment improvement and visual comfort are important.

The curved window showed the best results in cooling performance (18.2% reduction) and daylight performance (UDI 75%). However, the 8.2% increase in heating load acts as a critical drawback considering Pyongyang's long winters. Therefore, the curved window should be applied selectively to cooling-dominated buildings or spaces used intensively in summer, and additional insulation measures are essential to compensate for the degradation in heating performance.

### Design Guidelines for the Pyongyang Climate

The Pyongyang (Dwa) climate has long and severe winters, meaning heating load accounts for the majority of annual energy consumption. Therefore, when selecting window forms, winter heating performance should be prioritized over summer cooling performance. Based on the results of this study, the following practical design guidelines are proposed.

**General Office Buildings:** It is recommended to adopt the polygonal window as the basic form. It offers the best balance between cooling and heating performance, and stable annual energy performance can be expected without additional design modifications.

**Cooling-Dominated Buildings (e.g., commercial facilities, data centers):** The application of curved windows may be considered, but it must be accompanied by the use of high-performance insulation or the introduction of double-glazing systems to prepare for the increase in winter heating load.

**Spaces Prioritizing Daylight Performance (e.g., design studios, galleries):** Curved or protruded windows are suitable. Curved windows are advantageous for maximizing daylight quantity, while protruded windows are advantageous for minimizing glare; the choice depends on the specific use of the space.

### Research Limitations and Future Research Directions

This study was conducted on a single-zone model and may not fully reflect the complex thermal behavior of real buildings. Furthermore, variables other than window form (frame material, window system, shading devices, etc.) were not considered, so future research requires multi-objective optimization integrating these variables.

For follow-up research, the following extensions are proposed. First, it is necessary to generalize the climate dependency by comparing and analyzing the performance of identical window forms across various climate zones (cold, temperate, tropical). Second, a comprehensive energy performance evaluation is required that also considers the power generation performance of window forms integrated with BIPV systems. Third, there is a need to develop a methodology for quantifying formal value and visual comfort through actual user evaluations.

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