BauSIM 2022 in Weimar
20.-22. September 2022
Bauhaus-Universität Weimar
ibpsa

A FASTER METHOD FOR THE SIMULATION-BASED PARAMETRIC OPTIMIZATION OF STRUCTURAL SHADING

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Abstract

Optimal shading provides effective shielding of solar radiation to prevent overheating, while ensuring the use of solar gains. To achieve this goal with structural shading elements, a common method is to find the ideal parameters using time-consuming thermal simulations to evaluate possible shader dimensions. In this paper a new method was developed that requires a single ideal thermal reference simulation. Following the simulation the TRNSYS beam solar pre-processing and simulation processes were used to generate the optimal structural shading parameters instead of just evaluating them. The function of the developed method was demonstrated through the successful application to a single zone model.

Introduction

Shading systems are designed to reduce energy demand for heating and cooling while optimizing the users' comfort. This is achieved by providing effective shielding of solar radiation to prevent overheating in the warm season, while ensuring the use of solar gains in the cold season.

There are two main characteristics of solar shading systems, related to the possibility for the user to control the system – structural systems, where the user has no control and dynamic systems, where in most cases the user can exert influence (Urbano, R., Andersen, M., 2008). A structural sunshade should achieve the right configuration for optimal impact on energy demand and comfort through placement and dimensions. A dynamic solar shading system can be adapted to the different requirements manually (dynamic manual) and through motorised devices controlled by the user (dynamic automated) or automatically controlled by temperature and irradiation sensors (dynamic passive).

Many studies state that dynamic solar shading systems have a better performance in terms of energy demand and comfort in a building than structural systems. According to Kirimtat et al., who reviewed studies on shading devices, most of the studies (54 %) were done theoretically, based on a simulation and not experimentally (Kirimtat et al., 2016).

While the actual performance of structural shading elements can be mapped accurately in a simulation, the evaluation of dynamic systems turns out to be more difficult. Simulation results of dynamic shading performance often differ significantly from actual performance values demonstrated in an experiment.

This deviation arises mainly from the following factors. The performance of dynamic shading systems is strongly dependent on the control strategy adopted. A dynamic passive system controlled by environmental changes represents the optimal case and is often used in simulation. A loss of performance of dynamic passive control strategies, as Skelly and Wilkinson point out, is due to the control strategy being too complex. In the implementation they require multiple sensors for their operation, which are difficult to design and install (Skelly, M., Wilkinson, M., 2001).

The other factor that affects the optimal operation of the dynamic shading systems is user behavior. User responses to the dynamic shading system are inevitable. The possibility to control the conditions of their environment contributes to the users' comfort and well-being. At the same time, user behavior is responsible for discrepancies between the calculated performance of the sunshade and the measured values in the implementation, as it is often not well represented in simulation models (Van Den Wymelenberg, K., 2012). Adjusting the position and tilting angle of the dynamic sunshade results in a significant decrease in performance in the operation. The user cannot be relied upon to adjust the shading element every time it is desirable for energy reduction and comfort (Mahdavi et al., 2008).

Structural solar shading systems are not influenced by users and can be implemented with little technology. To optimize the performance of structural shading elements, a common method is to find the ideal parameters for size and position using evolutionary solvers. The configuration of the shading geometry can be changed parametrically and serves as an input for a building performance simulation. To find the optimal configuration, genetic algorithms embedded in an evolutionary solver are applied to evaluate the results of the simulations and control iteration parameters. This optimization process requires large computer processing capacity and simulation time (González, J., Fiorito, F. 2015).

In this paper a faster way for the simulation-based parametric optimization of structural shading elements is presented. To avoid time-consuming simulations for each possible shading configuration, a new method for generating an optimal geometry was developed.

Methodology

TRNSYS is a transient systems simulation program with a modular structure. The methodology presented in this paper is based on the TRNSYS beam solar pre-processing and the related simulation process.

In TRNSYS, beam radiation shading due to structural shading geometry is evaluated through solar angle dependent sunlit factors of the external windows. These factors are generated as part of the simulation pre-processing routine. Hereby, the sky is represented by a dome (Hemisphere), with the building placed at its center. The dome is subdivided into patches. The patch centerpoints are defined as sun positions. For each patch a sunlit factor is computed and saved in the "Shading Matrix" (SHM). In the Simulation the SHM is read. The actual sunlit fraction of each timestep is determined by bilinear interpolation of the four nearest center points with respect to the actual sunposition (Aschaber, J., Hiller, M., Weber, R. 2009).

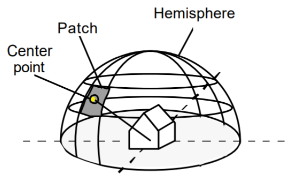

Figure 1 Discretization of the sky hemisphere (Aschaber, J., Hiller, M., Weber, R. 2009)

However, these simulation processes were used to find the optimal structural shading parameters instead of just conventionally applying them for building performance evaluation. Following the results of one ideal building performance simulation (reference simulation) only, they are applied to calculate the associated input parameters. Hereby, the related simulation processes were reversed.

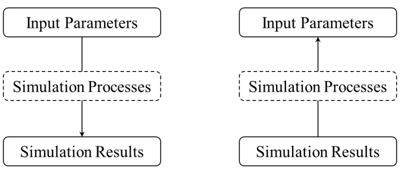

Figure 2: Conventional and presented use of simulation processes

All developed sub-programs of the workflow described in the following sections can be parametrically controlled from a single interface in Grasshopper (visual scripting for Rhino). In the interface, parametric inputs (e.g. building geometry or schedules) can be specified, calculations (e.g. building performance simulation in TRNSYS via the connector TRNLizard and developed sub-programs) can be started and results can be displayed.

Reference Simulation

The methodology requires the simulation results of a single ideal reference simulation with a dynamic passive shading system.

It was investigated using a single zone (27 m^2) that is oriented in north-south direction. The window to be shaded is located in the south wall and has an area of 4.5 m^2. There are no structural shading elements, such as surrounding buildings.

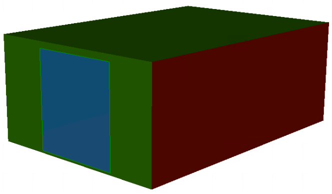

Figure 3: Single zone model

Properties of construction, internal loads, occupancy, and schedules are based on standard values from the SIA 2024 (Schweizerischer Ingenieur- und Architektenverein. 2015). The weather file (Wuppertal, Germany) has been collected from the Climate Data Center of the Deutscher Wetterdienst (DWD).

The goal of the set control strategy was to minimize heating energy demand and operative temperature Kelvin hours over 26 °C. Particular emphasis was placed on the control strategy of the shading system. The reference simulation was simulated with a passive dynamic shading system, which is representing the optimal shading case. The dynamic shading is controlled only based on the indoor temperature (operative temperature), the irradiance on the facade and the seasons according to the following approach:

$$Y_{shd} = Y_{temp} \cap (Y_{irr} \cup Y_{seas}) \quad (1)$$

Y_{shd} = shading signal; Y_{temp} = signal based on temperature; Y_{irr} = signal based on irradiation; Y_{seas} = signal based on seasons.

The solar protection is activated when either the operational temperature or irradiation control signal is True, while at the same time the seasonal signal is True. The values for the control strategy are described in more detail in *Table 1*.

Table 1: Control Strategy Dynamic Shading with Hysteresis Control

PARAMETER	VALUE
Y_{temp}	True: $T_{op} > 24°C$ False: $T_{op} < 22°C$
Y_{irr}	True: $I_{bW} > 180$ W/m² False: $I_{bW} < 120$ W/m²
Y_{seas}	True: $T_{amb,mean,24h} > 12°C$ False: $T_{amb,mean,24h} < 12°C$

T_{op} = operative temperature; I_{bW} = beam irradiation on window; $T_{amb,mean,24h}$ = mean ambient temperature of the last 24 hours.

The outputs of the reference simulation, which are printed at each timestep (0.1 hours) and used for the generation of the shading geometry are the following:

The resulting shading signal [-] • Zenith and azimuth angle [°] • The (unshaded) specific beam radiation on the window [Wh/m^2]

Generation of the Shading Geometry

Using the reference simulation outputs, the structural shading configuration is generated through geometric evaluation only.

<u>Creation of Cumulative Beam Radiation Domes</u>

As a first step, two beam radiation domes are created, following Reinhart's extension of the Tregenza sky subdivision scheme (Bourgeois, D., Reinhart, C., Ward, G., 2008) (Tregenza, P., 1987). The first dome contains the cumulative beam radiation distribution and the second dome is the first dome weighted by the shading signal. A resolution of 2305 patches is chosen, as implemented for direct sky contributions by Bourgeois et al.

The beam radiation value of each timestep from "Simulation Results" is distributed to the four nearest patches by bi-linear interpolation (azimuth and zenith). In order to avoid "gaps" in the radiation dome, it is important that a timestep of between 5-10 minutes or less is used to obtain the radiation values (Marsh, A. Dr. 2019).

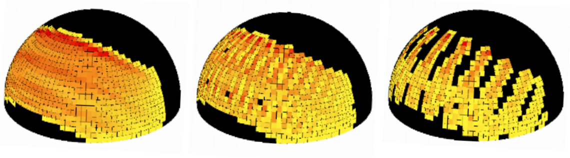

Figure 4: Cumulative beam radiation dome with timestep 0.1(6min), 0.5(30min) and 1(60min)

Conveniently, there is a radiation shaping algorithm implemented in TRNSYS18, that determines the solar radiation values at sub-hourly timesteps (McDowell et al. 2017). For this reason, the radiation values are extracted from the simulation output file and not the weather file directly.

If the shading signal for the corresponding timestep is "0" (shade open), the radiation value is multiplied by "1" and considered as desired solar radiation that aids in decreaseing the heating demand of the zone. If the shading signal is "1" (shade closed), the radiation value is multiplied by "-1" and considered undesired solar radiation that causes the building to overheat.

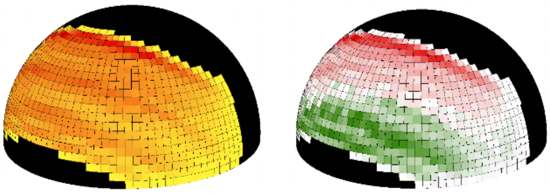

Figure 5: Left: cumulative beam radiation dome (scale: low - yellow, high - red); right: weighted by shading signal (scale: undesired - red, desired - green)

<u>Geometry Pre-processing</u>

The Geometry Pre-processing is an evolution of recent Trnsys Type 56 short wave radiation preprocessing developments (Hiller et. al., 2021). The adapted Pre-Processing contains three steps:

1 • Determination of possible shader locations and base shapes • A planar surface that represents the maximum possible shader dimension for each possible shader location is specified (These surfaces are called "ParBase" from hereon). The shape of the ParBase is a design decision, made by the user. The example shown in *Figure 6*, features a diamond shape.

2 • Conversion to Radiance geometry • Radiance materials and identifiers are assigned to the geometry from the reference simulation and a radiance scene is generated. If present, the context shaders (e.g. surrounding buildings) are to be included. The ParBase surfaces are added to the radiance file as a "trans" Material with 100 % transparency.

3 • Discretization of the window surface • The window surface is discretized into a quad mesh with uniform edges. Each mesh face area is represented by a grid point at its center. The grid spacing is defined by the user. As a default value, a spacing of 0.1 m is used.

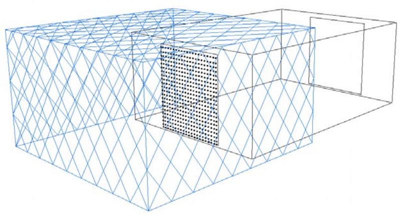

Figure 6: ParBase surfaces (blue) and window with grid

Calculate Area Matrix

A geometric Area Matrix (A), with a column for each ParBase and a row for each skypatch is created. Each entry is the sunlit area of the window that passes through the given ParBase surface (PB) from the given skypatch (α). This purely geometric matrix of all ParBase surfaces does not have to be regenerated if the non-geometric part of the reference simulation is changed (e.g. different control strategy or adjusted internal loads).

Using Radiances rtrace subroutine (Ward, G., Shakespeare, R., 1998), a ray is shot from each grid point (β) to each sky patch (α). If the weight of the ray at the end of its path ($wgrid_{\alpha,\beta}$) is above 0, the grid point is fully or partially (transparent context elements) sunlit. The window area that is represented by the grid point ($Agrid_{\alpha,\beta}$) is multiplied by the weight of the ray ($wgrid_{\alpha,\beta}$) and assigned to the ParBase surface that was permeated. This process is repeated for all gridpoints ($n_{gridpts}$) and skypatches.

$$A_{\alpha,PB} = \sum_{\beta=1}^{n_{gridpts}} Agrid_{\alpha,\beta} * wgrid_{\alpha,\beta} \quad \textbf{(2)}$$

Combine Cumulative Beam Radiation and Area Matrix

The specific beam radiation values (I_{α}) for each skypatch determined earlier (cumulative beam radiation dome) are multiplied element-wise with each collumn of the Area Matrix (A) and summed up. The result is the total annual radiation that enters through each ParBase polygon and hits the window (I_{PB}).

$$I_{PB} = \sum_{\alpha=1}^{n_{skypatches}} I_{\alpha} * A_{\alpha,PB} \quad \textbf{(3)}$$

The same steps are taken for the weighted radiation values (Iw_{α}) determined earlier (radiation dome weighted by shading signal).

$$Iw_{PB} = \sum_{\alpha=1}^{n_{skypatches}} Iw_{\alpha} * A_{\alpha,PB} \quad \textbf{(4)}$$

The following figure shows a visual representation of the annual radiation values of each ParBase.

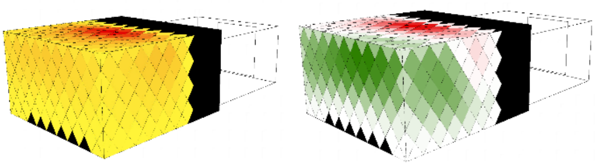

Figure 7: Left: annual radiation values for each ParBase polygon (scale: low - yellow, high - red); right: weighted by shading signal (scale: undesired - red, desired - green)

Determine Scale Parameter of Shading Elements

Lastly, the area for each shading element (A_{shdr}), placed at each ParBase, is determined. The corrsponding scale parameter (SF_{PB}) is calculated from the annual ratio of desired and undesired radiation entering through each ParBase.

$$SF_{PB} = -0.5 * \left(\frac{Iw_{PB}}{I_{PB}}\right) + 0.5 \quad \textbf{(5)}$$

The scale parameter is the area reduction from the maximum possible shader dimension, given by the ParBase surface ($Amax_{PB}$).

$$A_{shdr} = SF_{PB} * Amax_{PB} \quad \textbf{(6)}$$

The scaling parameter is a value between 1 and 0.

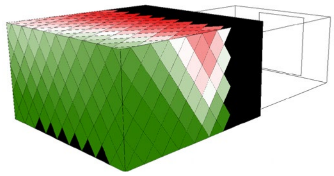

Figure 8: Scaling parameter visualization for each ParBase (scale: green - 0 ; red - 1)

A value of 0 corresponds to no shading element at all and 1 corresponds to a fully filled ParBase. The following figure shows the final scaled shading elements.

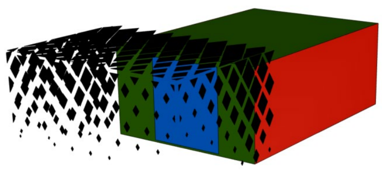

Figure 9: The final scaled shading elements

Comparison of Reference and Structural

The generated structural shading geometry is added to the zone as a "shading group" in the 3D TRNSYS building model. The shading matrix is generated to obtain solar angle dependent sunlit fractions for the external window. The model is simulated and the performance is compared to the reference simulation in terms of operative temperature Kelvin hours over 26 °C and heating energy demand.

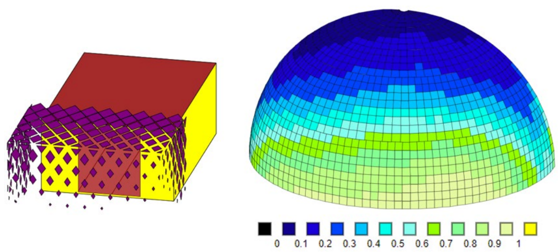

Figure 10: trnView screenshot; visual representation of the shading matrix

To put the results into context, the zone is simulated without any shading first, resulting in an annual heating demand of 41.48 kWh/m² and 1157 Kh overheating hours. The annual heating demand of the considered zone with dynamic shading (Qht_dyn) is 41.98 kWh/m^{2}a and the overheating hours (Kh_dyn) are 471 Kh. With the generated structural shading, these values deviate by about +2 kWh/m^{2}a (Qht_stat) and +200 Kh (Kh_stat) from the results featuring dynamic shading.

The months that feature the highest relative deviation (percentage error) of the heating demand from the reference simulation are part of the shoulder season (May and Octotber), as seen in *Figure 11*.

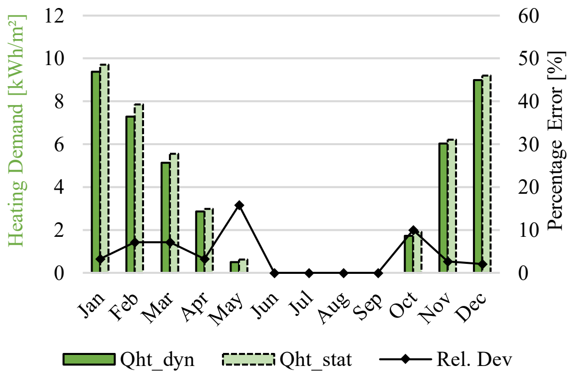

Figure 11: Absolute and relative deviation of heating energy demand

The relative deviation of the overheating hours (Kh_dyn and Kh_stat) follows the same trend. As seen in *Figure 12*, the months with the largest relative deviation percentage are also part of the shoulder season (May and September).

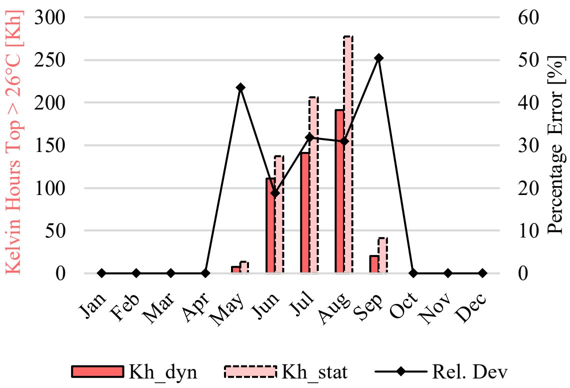

Figure 12: Absolute and relative deviation of overheating

The shoulder season features days, where periods with desired and undesired beam radiation are alternating. Therefore, the shading elements corresponding to these solar position are scaled in accordance to the best balance. This means that during shoulder seasons, momentary deviations of the surface beam radiation on the window are alternating between positive (too much shading) and negative (too little shading), as seen in *Figure 13*.

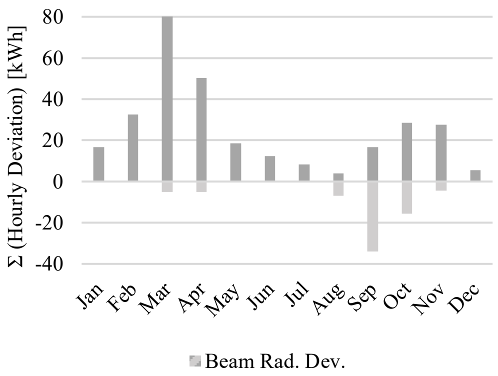

Figure 13: Summed up hourly positive and negative deviation of beam radiation

However, the majority of the shoulder season is not problematic in terms of overheating hours, since solar gains and other heat loads can be removed with natural ventilation.

As seen for two September days in *Figure 14*, the shading factor of the structural shading system (FS_stat) is significantly lower than the one of the dynamic system (FS_dyn). Yet, the operative temperture (Top_dyn and Top_stat) stays within the same range.

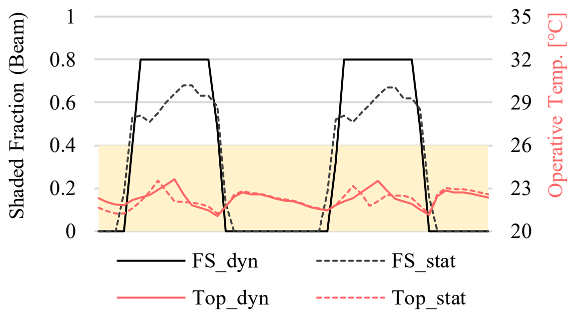

Figure 14: Shaded fraction and operative temperature for two days in shoulder season

This is because the ventilation (ACH_dyn and ACH_stat) in the structural case is activated earlier, as seen in *Figure 15*.

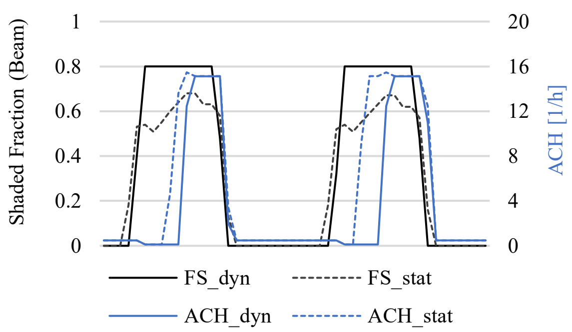

Figure 15: Shaded fraction and air changes per hour (ACH) for two days in shoulder season

- The beam shading factors for the static system deviate the most from the dynamic ones in the shoulder season due to an overlap in desired and undesired radiation at similar sun positions.
- The shoulder season is not problematic in terms of overheating, as solar gains can be removed by natural ventilation

The majority of the absolute performance gap of 200 Kh does not occur in the shoulder season. It occurs in the months of July and August, which feature the smallest beam radiation deviation, as seen in *Figure 13*.

During July and August, there is almost only undesired radiation. Therefore, the scaling factor of the corresponding shading elements is large. As seen for two August days in *Figure 16*, the dynamic shading factor (FS_dyn) matches the structural shading factor (FS_stat) very closely.

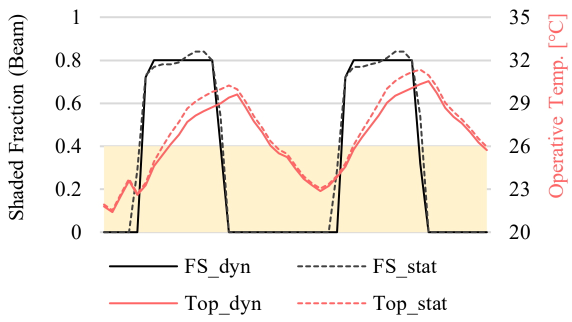

Figure 16: Shaded fraction and operative temperature for two summer days

This corresponds directly to the incident shaded beam radiation on the window ($IBSHAD\_dyn$ and $IBSHAD\_stat$), as seen in *Figure 17*. The values for dynamic and structural shading are in very good agreement. However, there is still a difference of up to one Kelvin in terms of operative temperature ($Top_{dyn} - Top\_stat$).

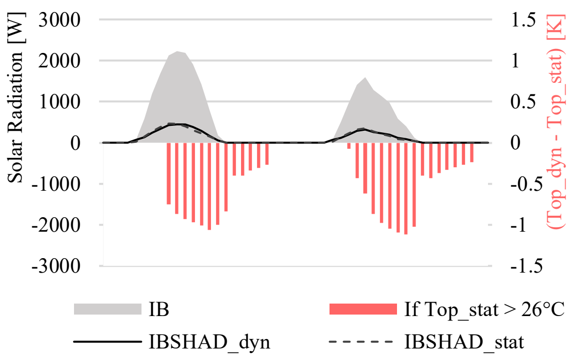

Figure 17: Incident (shaded) beam radiation and Kelvin hours deviation for two summer days

This deviation in operative temperture results from the diffuse radiation (ID). The dynamic shading shields more indcident diffuse radiation than the structural shading system ($IDSHAD\_dyn$ and $IDSHAD\_stat$), as seen in *Figure 18*.

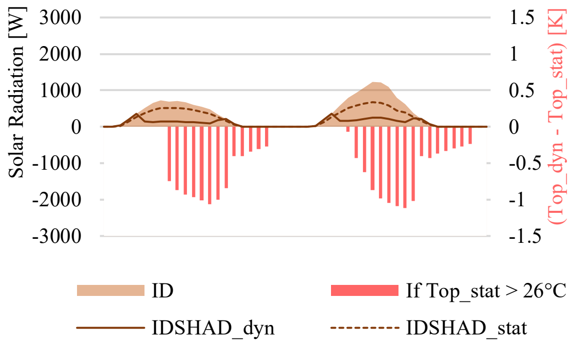

Figure 18: Solar (shaded) diffuse radiation and Kelvin hours deviation for two summer days

- The static shading system replicates the direct beam radiation shading factors of the dynamic system very closely during June, July and August.
- The absolute difference (performance gap) of overheating hours of reference and static simulation is highest during June, July and August.
- The majority of the overheating performance gap results from diffuse radiation.

Conclusion

In this paper the TRNSYS beam solar pre-processing and simulation processes were used to find the optimal structural shading parameters instead of just evaluating them.

The developed workflow and its sub-programs were implemented into an interface and its function was demonstrated through the application to a single zone model.

An optimized structural shading configuration was generated with the developed methodology. The performance of the reference simulation with passive dynamic shading control surpasses the structural shading system to a tolerable extent. However, the ideal passive dynamic control used in the reference simulation is error-prone in actual building operation. This would lead to a decrease in performance for the dynamic system while the performance of the structural system remains the same.

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