Parametric Modelling Using the Operative Temperature Map for Façade Design of Office Buildings

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Abstract. Controlling incoming solar radiation to a building is one of the main targets of sustainable architecture designers because it decreases HVAC energy consumption and maximizes thermal comfort and usable daylight. The introduction of parametric design has allowed designers to expand their approaches to explore possibilities in façade forms and systems. However, most solar shading designs with complex geometries have been rejected by such building performance simulation software as *Energyplus* when assessing the calculation of thermal loads.

To overcome this limitation, this research introduced a new framework using the Rhinoceros platform to simulate radiant discomfort across spaces with various types of parametric façades. The framework was established based on the ASHRAE55 appendix and improved the longwave MRT calculation by using the Radiance-based pre-processing method. The use of an operative temperature (OT) map was then highlighted as a measure of the combined effect of mean radiant and air temperatures considering the conditions of air velocity and relative humidity in office layouts. Designers were able to compare the hourly intensity of solar radiation passing through a façade between different design cases. Furthermore, the metric of Annual Thermal Discomfort Hours (ATDHs) and the Spatial Thermal Comfort Availability (sTCA) index were proposed for assessing the effect of solar radiation throughout a space. These dynamic indexes were adopted to evaluate different scenarios using the local climate thermal comfort statistics. Eventually, the simulation framework was validated by a field experiment which showed a high accuracy by R^2=0.91. By the proposed study, designers can involve critical thermal sensation factors in the early design stage regardless of the complexity of the parametric facades.

Keywords. Indoor thermal comfort, solar radiation, subtropical.
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1.Introduction

As an improvement to office building design in order to increase natural daylight, floor-to-ceiling glazing on the façade in office design is gaining favor with modern architects. However, with the warm subtropical climate in Taiwan, large openings create serious issues by admitting large amounts of solar, especially shortwave, radiation indoor [1]. The landing of uncontrolled solar radiation directly on occupants can lead to considerable indoor thermal discomfort that the HVAC system cannot handle. Therefore, in buildings with a high wall-to-window ratio (WWR), the critical assessment for thermal comfort is the daylit perimeter zone near the facades [2].

Radiant temperature is of great importance when assessing thermal comfort. Incoming solar radiation, which comes in the form of direct, diffuse, and reflected beams, is responsible for solar heat gains absorbed by building envelopes, as well as localized temperature rise in the overly lit area, consequently leading to an increase of the mean radiant temperature (MRT). The occupants are thus forced to deploy additional shading; otherwise, the thermal perceptions may change beyond the acceptable range. Due to a lack of simulation methods and standards, not until recently did the ASHRAE55-2017 adopt the Solar Calculation Method based on Arens's study [3], which was then implemented in Ladybug Comfort Component [4] to provide a parametric module for designers.

External shadings attaching to the façade can simultaneously shade the solar radiation and improve a building's energy efficiency, while still maintaining a high level of architectural and aesthetic quality [5]. Thus, designers in Taiwan embrace double skin façade such as perforated metal board, louvers and expanded metal lathes. On top of that, parametric software that acts as a graphical algorithm editor and allows designers to generate parametric forms has also been introduced and has been used to combine different dimensions and proportions with building performance simulation plugins [6]. However, when encountering complex forms, designers need to conduct considerable simulation work and often fail to import a model that restricts the function and accuracy of the simulation results.

In this research, a new simulation framework is illustrated based on the Rhinoceros-Grasshopper platform to expand the possibility of the simulation process when encounter complex double skin façade geometries.

2.Method

2.1 Simulation Framework

In this section, the workflow (**Error! Reference source not found.**) is presented to introduce the Diva plugins into the calculation of adjusted MRT (ΔMRT) and explain how to post-process the results to assess the thermal comfort index using spatial distribution and a climate-based adaption model.

We first defined complex façade geometries and chosen location, which were later transformed by the presented pre-processor. Consequently, the performance of the facade on MRT was calculated using the *SOLcal* model and *EnergyPlus* heat balance method, which generate both the effect of shortwave and longwave solar radiation. Finally, the results presented in operative temperature (OT) were processed into dynamic indexes to assess thermal comfort.

2.2 Description of the test case scenario

The model replicates a single-room office space located in Taipei (latitude 25.1054°N, longitude 121.5973°E). A reference model measuring 15 m×10 m and 4m in height was modelled using Rhinoceros-Grasshopper software, as shown in **Fig. 2**. The west wall was set as a floor-to-ceiling glaze since this study was focused on the solar radiation effect of

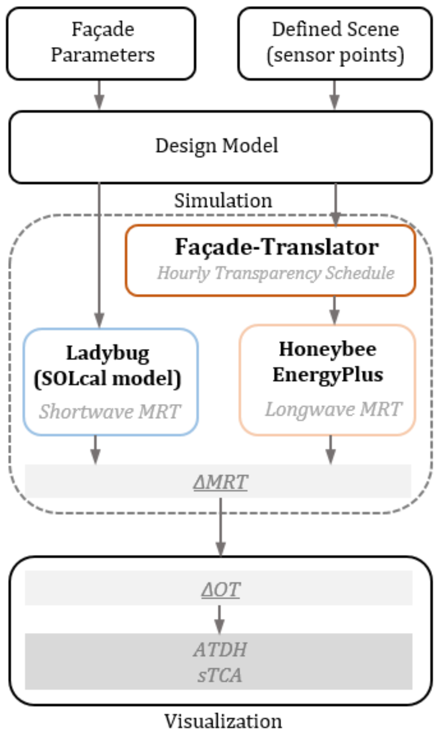


Fig. 1 - Simulation framework

façade design.

The target surface was set to 0.75 meter from the floor to represent the central point of the sitting human body. The lifted surface was a frame with a grid of 0.5× 0.5 m, which divided the space by human scale.

The thermal and radiative properties set for the elements are shown in **Error! Reference source not found.**. In order to guarantee a thermally neutral starting condition, an ideal HVAC was modelled with $T_{heating}$ = 23°C, $T_{cooling}$ = 26°C. All windows were assumed to be closed, and the infiltration rate was set to as low as 0.0001. According to office use, internal load density is defined as equipment (10W/m^2), lighting (20 W/m^2), and people (0.2 ple/m^2), considering working hours of 9:00 to 18:00. The hourly schedules for the internal heat sources were illustrated in **Fig. 3**.

2.3 pre-processor

In order to model the thermal performance of the

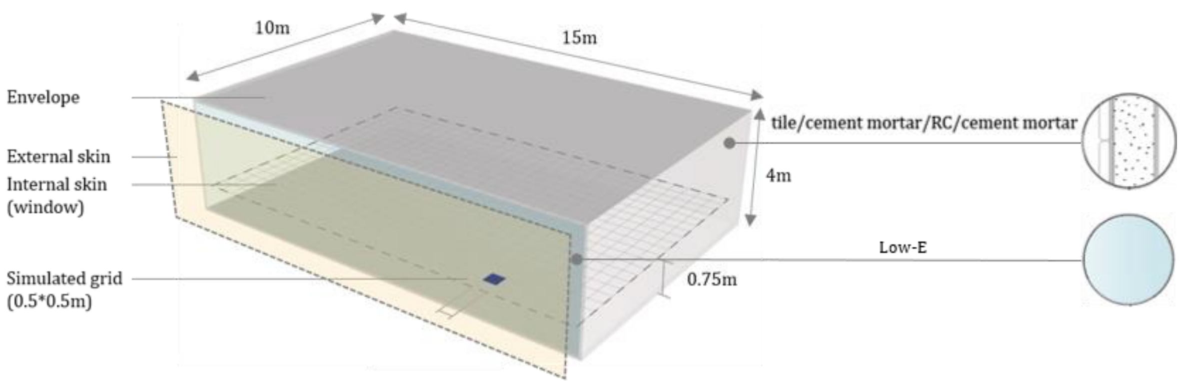


Fig. 2 - Description of the base model

Tab. 1 - Base model material properties

Element	description	Value/ properties
Exterior wall	Solar reflectance	0.5
	Material	adiabatic
Floor	Solar reflectance	0.2
	Material	adiabatic
Ceiling	Solar reflectance	0.8
	Material	adiabatic
Glaze	Solar reflectance	0.7
	Visible transmittance	0.542
	Solar heat gain coefficient	0.424
	Thermal transmittance(U-value)	1.81W/m^2
Façade shading	Solar reflectance	0.7
	Material	Hourly Transparency Schedule

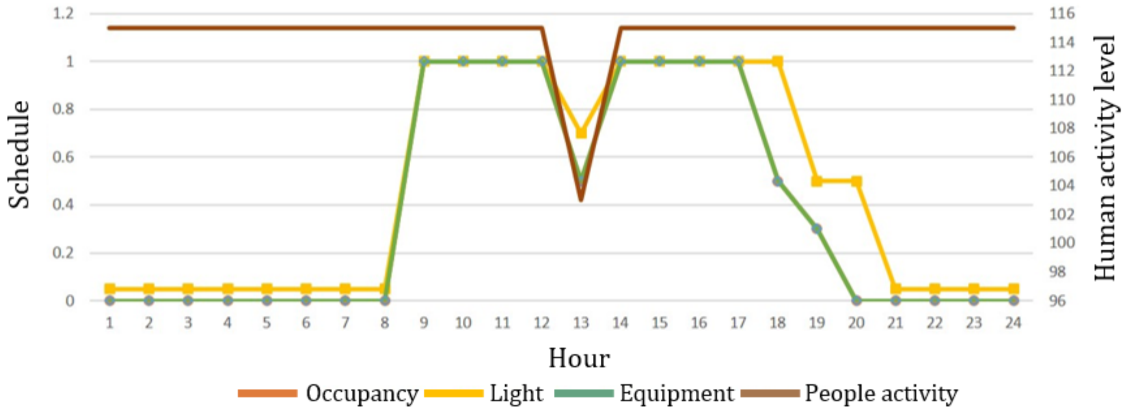


Fig. 3 - Occupancy Schedule

double skin façade, we developed a specific calculation process that coupled the advantages of Energyplus software with the potential of DIVA plugins concerning characterizing complex geometries with ray tracing methods. First, solar radiation was simulated using the TMY3 weather file (.EPW) on a vertical mesh attached to the glazed façade with 160 sensors arranged in the grid of 0.5 m × 0.5 m, as shown in **Fig. 4(a).** Secondly, the shading transparency coefficient was generated according to the ratio of the value of solar radiation with and without the portion of façade. The closer the coefficient value was set to 0, the more effective the thermal efficiency of the façade was (**Fig. 4(b)**). The annual radiation transparency schedule was then compiled into an hourly transparency schedule with 8760 value and connected to the HB_context module in the Honeybee plugins. The Honeybee plugins work as an interface to connect parametric design platform (Rhino-grasshopper) with Energyplus.

2.4 Solar-adjusted MRT calculation

This study applies the Solar Calculation model (SOLcal) developed by Arens in 2015 [3] to calculate the solar-adjusted MRT (ΔMRT). The radiation derived from the sun was split into direct, diffuse and reflected radiation and consequently translate into an effective radiant field and into ΔMRT.

Operative temperature aligned with ASHRAE55 and ISO standards is a modified temperature for the feeling of the thermal environment. It states that air velocity and relative humidity were assumed to be stable in air-conditioned spaces such as office buildings. Therefore, OT is chosen to be a reasonable indicator of thermal comfort indices that represent the effect of both air temperature and ΔMRT.

We use the "indoor micro-climate map" component in the Ladybug module [7] to calculated the ΔMRT

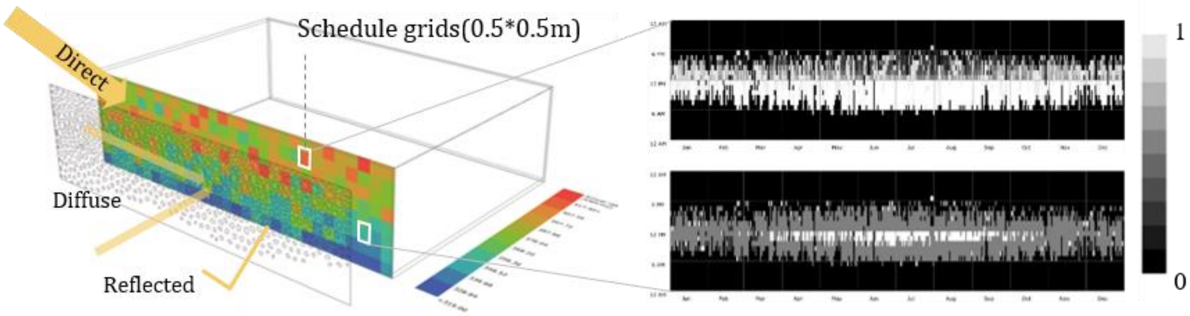


Fig. 4- Pre-processor:(a)schematic diagram of daylight transmission (b) hourly transparency schedule

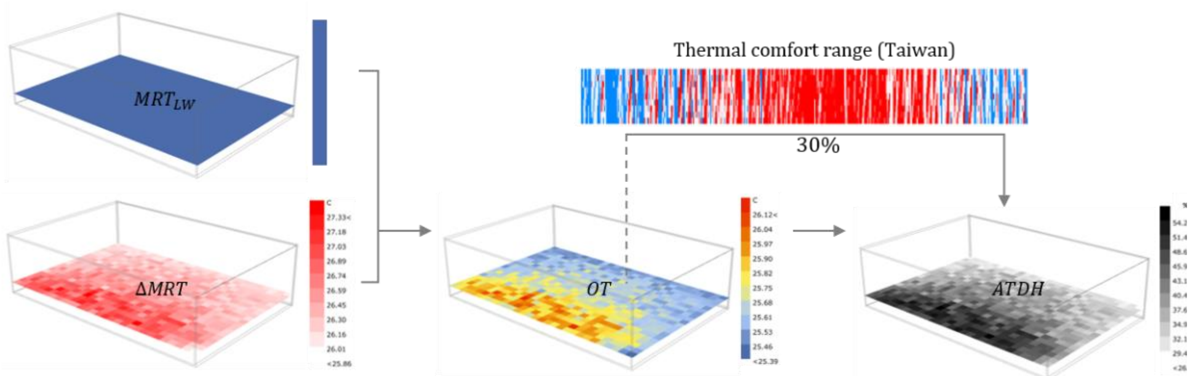


Fig. 5 - Detailed procedure of the OT and ATDHs map

based on the simulation framework described in paragraph 2.3. Significant variations of the distribution of the indoor OT were found according to the example façade pattern, as shown in **Fig. 5**

2.5 thermal comfort assessment

Adapted thermal comfort range varies depending on several essential factors, climate zones, race and gender, for instance. Accordingly, the acceptable thermal comfortable range was defined based on the field experiments, conducted in 29 air-conditioned offices with 650 individuals in Taiwan [8]. Responses from those subjects suggest a comfort temperature range of 23.8–27.5ºC that shifts to slightly warmer temperatures by about 0.5ºC as compared to the comfort zone recommended in ASHRAE standard 55 [9].

Performance metrics can be used for comparative studies to guide building design or to benchmark a building against a pool of other buildings. On top of that, dynamic metrics such as sDA and ASE include spatial and temporal consideration can better adopted by building certification systems.

The annual thermal discomfort hour (ATDH) was then developed as a dynamic index [10]. This metric can be described as the percentage of working hours that are above the acceptable thermal comfortable range. This comfort range indicates that occupants in Taiwan have adapted to the area's hot and humid climate. For acclimatized people, ATDHs can be applied as shown in equation (1).

$$\text{ATDH} = \frac{\sum_n (wf_i \times t_i)}{\sum_n t_i} \in [0,1]$$

$$\text{wfi} = \begin{cases} 1 & \text{if Cot} \notin [23.8 - 27.5°\text{C}] \\ 0 & \text{if Cot} \in [23.8 - 27.5°\text{C}] \end{cases} \quad (1)$$

where t_i is each occupied hour in a year, and C_{ot} is the hourly value of operative temperature for each point presented in the grid.

To assess the annual scenario between various façade design candidates, an example of the spatial map of ATDH is presented in **Error! Reference source not found.**(a). Without the influence of air velocity and relative humidity, indoor thermal indices were dominated by solar radiation, where the occupants near the façade were forced to apply extra

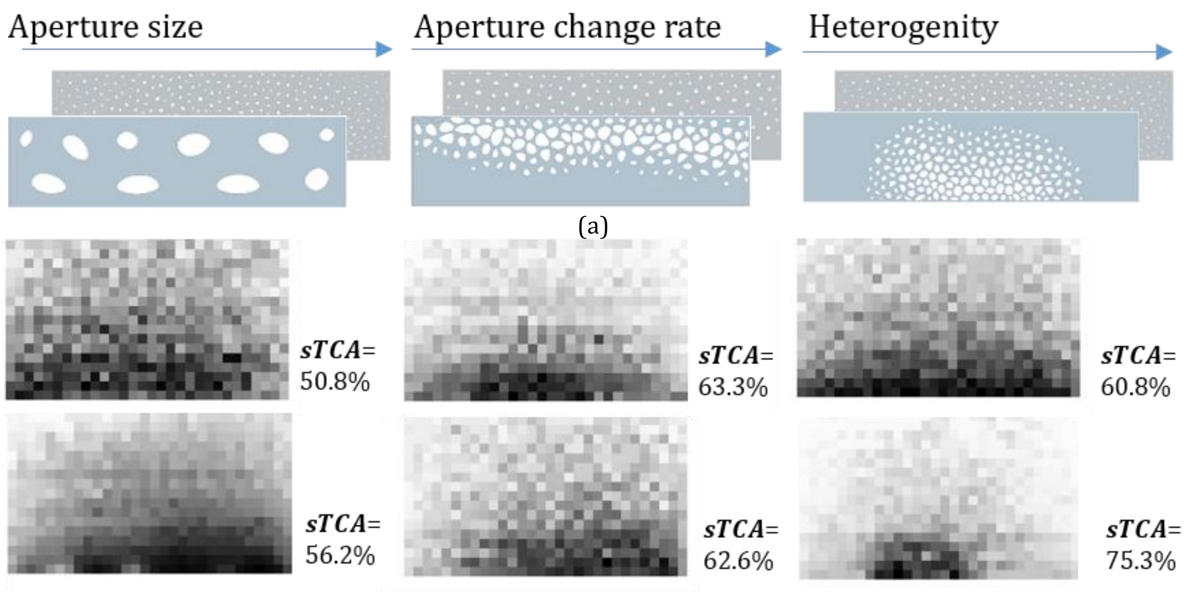
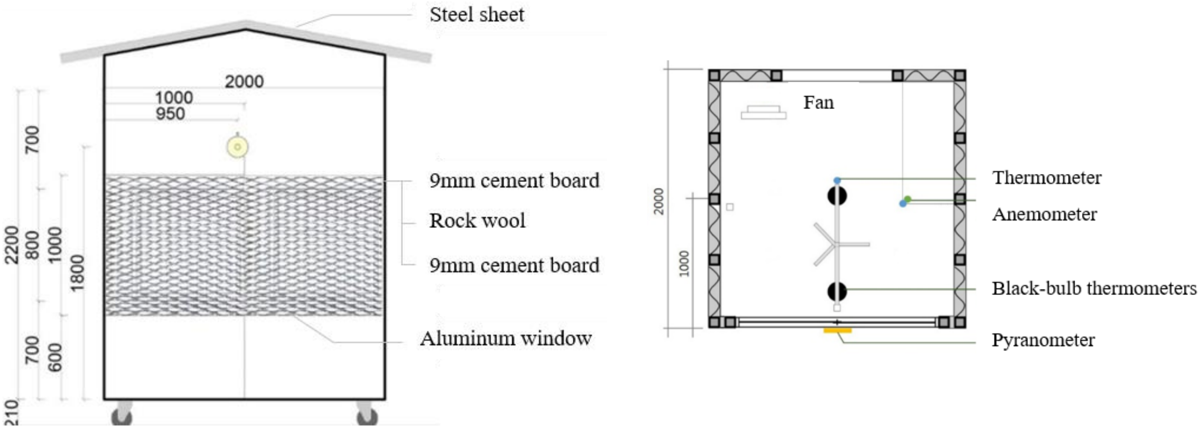


Fig. 6 - (a) The diversification of the Façade (b) Examples of indoor ATDHs distribution



(a) (b)

Fig. 7 - Field measurement configuration: (a)material and dimensions, (b)plan and equipment

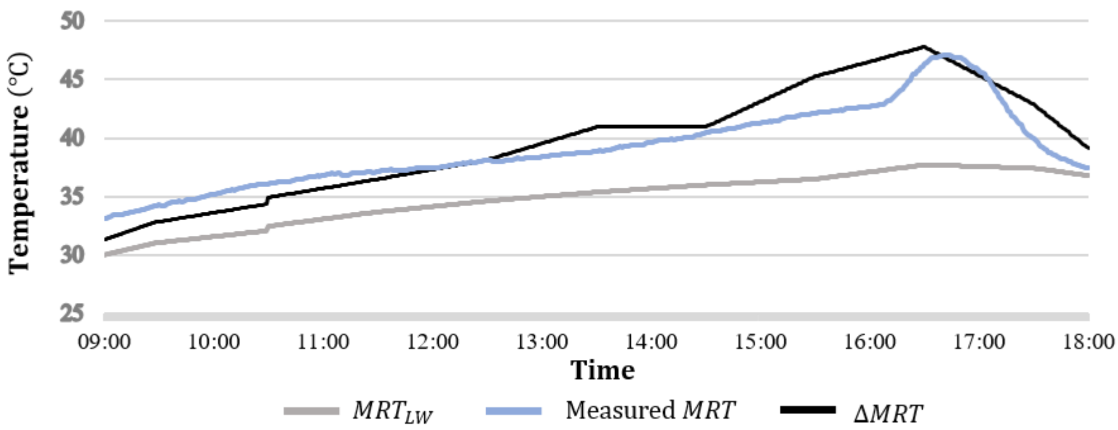


Fig. 8 - MRT comparison between field measurement and simulation

shading.

Furthermore, the results obtained with the thermal comfort range were compared by means of the long-term metrics -of Spatial Thermal Comfort Availability (sTCA) shown in equation (2). The sTCA expresses the partition of space with a threshold comfort range, which is 80% of perception according to a previous study [11]. This metric could significantly benefit architects and owners. Architects can use sTCA analysis to evaluate different design alternatives to determine which concept provides a better thermal environment in the interior, as shown in **Fig. 6**(b).

$$\mathrm{sTCA}_{80} = \sum_{i}^{N} \mathrm{wfi} \frac{1}{N} \in [0,1]$$

$$\mathrm{Wf_i} = \begin{cases} 1 \text{ if ATDHi} < 10\% \\ 0 \text{ if ATDHi} > 10\% \end{cases} \quad (2)$$

3.Validation

3.1 validation of the simulation model

To verify the simulation framework, we conducted a field measurement at National Cheng Kung University, Tainan. An experimental house was constructed with the dimensions of 2 m×2 m×2.2 m. The only opening of the house is 1.9 m×1 m covered with an expanded aluminum mesh, and the orientation was set to the west. The perforated rate of the metal mesh was 70%. The MRT was measured through two black-bulb thermometers, two thermometers, and one anemometer, which were arranged as shown in Error! Reference source not found.. The time interval of data collection was ten minutes, and the experiments were carried out from 9:00 to 18:00 on October 10.

The simulation model replicated the experimental house and was tested using the proposed framework. The TMY3 data was replaced by measured data when the simulation was implemented.

Error! Reference source not found. shows the comparison of the measured results and the simulation outputs, with and without shortwave radiation. Both of the simulation results were in line with the increase of the MRT from 9:00 to 18:00. However, the black-bulb thermometer was affected by the direct radiation around 16:00, which caused a rapid increase in MRT value. The results of the proposed workflow were highly correlated to the measured value, with an R^2 value of 0.91.

4. Conclusions and Future Works

The results presented in the previous section prove the feasibility of the workflow. Parametric modelling façades were programmed in the Rhinoceros-Grasshopper platform, and the effectiveness of the double-skin facades were pre-processed into grids with an hourly transparency schedule, which overcame the limitation of Energyplus software when facing complex geometries. Furthermore, we established a thermal comfort model considering climate adaptation, which allows local designers to predict more applicable thermal sensations of the occupants across the room. Using an hourly operative temperature map and Annual Thermal Discomfort Hours distribution, early-stage performance evaluations are possible in combination with energy and daylight optimization by using parametric design.

The framework described in this paper opens up new research questions:

First, coupling the CFD simulation that introduces the impact of air flow may help to include the influence of wind velocity on thermal comfort in order to predict more realistic heat stress conditions.

Secondly, introducing such machine learning methods as random forest and artificial neural network with specific local data may reduce simulation time and accelerate the design process.

5. References

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Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.