Interaction between controlled natural lighting and IEQ: integrated double skin facades approach applied on an office building

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ABSTRACT
Double skin facades can be used as a balanced solution to facilitate natural lighting into buildings and control the amount of admitted solar radiation. This study aims to identify an optimal solution for daylight and energy performance within an office building by optimizing the façade's opening size and panel rotation. The goal is to generate a flexible model that contributes to the overall performance and thermal comfort.
The paper provides a methodology using parametric tools of Grasshopper via Energy-plus/ladybug to analyze and evaluate the thermal performance of different iterations of a double skin façade. Although various IEQ aspects affect comfort levels, few studies have investigated the interaction between IEQ and thermal performance levels regulated by double-skin façade.
The results concluded that the proposed skin facade could reduce 30% of the total radiation of the original office building. While, the rotation of the facade panels proved to be a significant factor as it resulted in the highest reduction in radiation, up to 32%.

INTRODUCTION

The building sector consumes more than half of its energy to achieve thermal comfort through heating and cooling systems (Young et al., 2018). Generally, the building envelope manages the transfer of exterior environmental elements into the indoor environment. It, in turn, provides environmentally efficient interactive buildings by fulfilling 80% of the building demands (Etman, et al., 2013). High energy consumption had called out the researchers' concerns to develop extensive studies dedicated to façade performance and its effect on energy consumption and thermal comfort.

Solar shading techniques provide the building with an envelope that balances daylight levels and solar radiation, controls the thermal exchange, and contributes to the annual energy savings (Bellia, et al., 2013). The systematic integration of shape, size and distribution of the envelope's pattern plays a crucial role in minimizing glare and maximizing daylight (Mirrahimi et al., 2016). The consumption of artificial lighting can be reduced depending on natural daylight as the primary lighting resource during the day (Baker, 2002). Natural light provides the occupants with a positive psychological and physiological effect (Tzempelikos, 2017). However, more aspects must be considered, such as the visual comfort and heat gain, to enhance the quality of the indoor environment because "nature is always in motion, never at a standstill" (Plummer, 1995).

Double Skin Facades (DSFs) can be provided with opaque panels to control the radiation and reflect direct sunlight, while the glazing part can give a clear view of the exterior (Aljofi, 2005). Accordingly, to provide a climatic adaptive design, it is crucial to analyze the relationship between space and other aspects that concern daylighting, such as lighting and radiance (Reinhart, 2011). A couple of parameters affect the building envelop performance, such as climate and building function (Sarkar & Bose, 2016). Therefore, it is essential to have optimal openings to improve daylighting while considering the accompanying negative effect of thermal gains and losses that may cause discomfort and increase energy consumption (Mahdavinejad, et al., 2012).

In architecture, the building's form determines the building identity and defines its environmental interaction; the building form can determine the admitted daylight amount into the building (ASHRAE, 2006). There are other alternative solutions to admit daylight into buildings, such as courtyards, atriums, lightwells, etc. (Baker, 2002). With the use of technological and innovative passive design strategies, which became readily available (Tang, et al., 2012), utilizing these opportunities at an early design stage will provide environmentally high-performance solutions and buildings. Nevertheless, it is complicated to assess the passive design strategies under different conditions, and computational studies are somehow inevitable to predict such a strategy's performance under various conditions.

'Parametric' is originally coming from 'parameter' and is defined as "any measurable factor that defines or limits a system" (Terzidis, 2009). Parametric design is concerned with tools that create and recognize a relationship between different sets of parameters in a model and allow the designer to adjust those parameters to analyze the model's reaction according to the modified data (Jabi, 2013). Therefore, parametric designs are known as defining a problem using variables that can be altered to determine the most suitable solution to the situation described. Parametric designs are widely used in contemporary design practices as they depend highly on computers. The parameters are generated through code writing and unique programming language (Hudson, 2010). Parametric designs are a crucial element to fulfil performance-related goals in performative architecture.

Parametric skin façade patterns are still being developed. The impact of parametric skin facades on daylighting performance has not been widely studied. Such a facade presents a complex coding process, making it more complicated to model using simulation tools. That makes the design process more intricate and sophisticated. Energy consumption tools like EnergyPlus are used mainly to assess the energy performance of entire building systems. Still, it lacks accuracy in describing the energy transformation through sophisticated geometry (Kim & Park, 2012). The software has a shortcoming in predicting daylight in the space, especially if the gap between the façade and space increases (Ramos & Ghisi, 2010). Researches tried to develop methods that would overcome this limitation using tools such as Rhinoceros/ Grasshopper (Lagios et al., 2010). Gonzalez and Fiorito combined parametric design with energy performance tools using Galapagos/Grasshopper and DIVA to calculate daylighting, energy consumption and CO2 omissions (González & Fiorito, 2015).

Previous works were dedicated to studying the effect of fixed shading systems like overhangs, fins and louvres on thermal performance by using energy simulation tools such as TRNSYS, EES and Energy-Plus (Gracia, et al., 2013, Aparicio-Fernández, et al., 2014, Bellia, et al., 2013). A few studies have focused on creating stability between reducing solar gains and efficient daylighting through solar control systems (Sherif et al., 2010, Pino et al., 2012). Other studies analyzed the balance between daylighting and thermal performance to reach design optimization through perforated skin facades (Chi et al., 2017) and with interactive kinetic skin facades (Hosseini, Mohammadi, & Guerra-Santin, 2019) and parametric patterns on office spaces (Rashwan, et al., 2019).

The scope of the study focuses on an office building in the Mediterranean climate in Turkey. Although the case study selected in this paper exhibits an extensive application of ecological strategies, the role of the double-skin façade in the office building was overlooked. This restriction caused discomfort and overheating in the interior spaces, especially in the laboratories located in the southern parts. That, in turn, forced the occupants to resort to active alternatives to achieve their thermal comfort, which increases energy consumption. As the users spend most of their day inside the building, it is crucial to develop an external building envelope to control the quality of the interior spaces in terms of daylighting and thermal comfort.

Although studies are conducted under this scope, they lack the strategical application of an optimized façade integrated with an office building located in the Mediterranean climate. In this procedure, the paper investigates an energy-efficient approach driven by double façade patterns through the strategical application of different iterations. The iterations tested in the parametric skin façade are based on the distance between panels and the rotation degree of the panels. The research analyses different façade patterns on office building units by evaluating their environmental performances to identify the optimum façade pattern. The optimized design aims to find an equilibrium between available daylighting and total radiation in an office building in Izmir, Turkey. The study mainly focuses on façade distance optimization and façade rotation optimization to balance energy consumption and occupants' comfort.

METHODS

The research is conducted with a qualitative method and investigated with a quantitative experiment. The experiment combines qualitative and quantitative characteristics of daylight radiation and its effect on the users' well-being and comfort. It will offer the occupants a better working environment and a comfortable space.

The presented methodology includes four main stages. Firstly, the modelling of the selected office area to conduct the study. The second stage consists of coding using Grasshopper (Freitas et al., 2020), a parametric modelling plugin for the 3D modelling program Rhinoceros (Groenewolt et al., 2016). Then the application of the proposed skin façade and its iteration on the modelled area. The following step consists of an environmental analysis conducted by using EnergyPlus (Crawley, et al., 2000). Ladybug (Roudsari et al., 2013) calculates solar radiation levels using EnergyPlus weather files and the cumulative sky approach (Ibarra and Reinhart, 2011). The presented methodology and software had been used in prior studies and verified through them (Groenewolt, et al., 2016; Freitas, et al., 2020).

Finally, a comprehensive analysis of the results was conducted. The analysis calculates the radiance performance in the modelled space area and compares it with the applied skin façade iteration results. The results include comparisons between the four different skin façade iterations and their performance. The presented steps are outlined in (Figure 1) and explained in detail in the case study.

Case study

The case study is an office building laboratory located in Izmir Province of Turkey. The climate is warm and humid. Izmir is specified with its long dry summers and short wet winters. It is categorised by Koppen and Geiger as Csa; Hot-summer Mediterranean climate (Kottek, et al., 2006).

The office building consists of 35 second-hand shipping containers designed to form one united "Catalyst". The catalyst consists of offices, laboratories and showrooms juxtaposed around an internal courtyard. Most of the laboratories are located on the southern part of the project (Figure 2).

Figure 2. Site plan of the office building. Source: Atoyle Architects.

A reference model of the highlighted laboratory (Figure 3) was modelled using Rhinoceros Software. According to the original measurements, the lab unit was modelled; 12m x 15m x 4m. The boundary space for the windows facing the north and the south are 1.5m from the floor and 2.3m in height (Figure 4& 5). The building envelope and material properties were not taken as a reference; the model's material and characteristics have not been considered in this study. All later simulations had the same fixed values for the features and material to dismiss the results' effect.

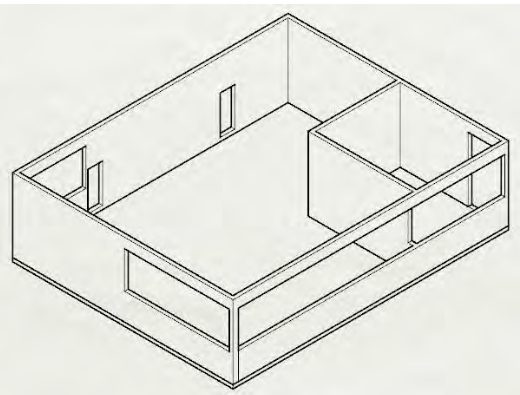

Figure 3. Modelled laboratory using Rhinoceros software.

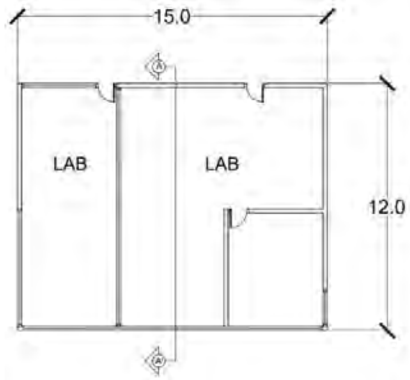

Figure 4. Plan of the modelled laboratory.

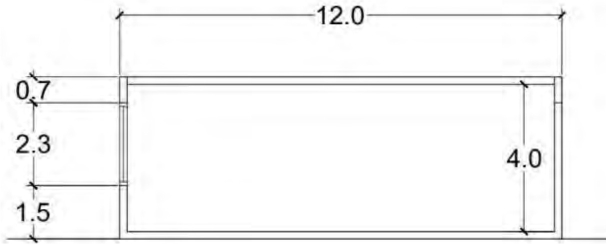

Figure 5. Section cut of the modelled laboratory.

Double-skin façade design

The parametric façade pattern was coded and modelled using Grasshopper plugin in Rhinoceros. It was added to the laboratory model and fixed at 300mm from the southern glazed windows externally. The modelled skin is 15m long and 2.3 m high in total. The materials and characteristics of the skin were not considered in this simulation. The performance of the skin façade is evaluated and determined by two main factors; panel size and panel rotation. The simulation had been run on four façade iterations: A, B, C and D (Figure 6). Table 1 shows the main characteristics of each iteration. It explains the distinction in the number of panels, the dimensions, the distance between panels and the rotation on the four different iteration designs A, B, C and D.

Table 1. The distinction between facade patterns. Facade materials and characteristic were not considered in this simulation.

Pattern number	Number of panels of the facade	Dimensions of each panel	Façade panels Rotation rate
Pattern A	10	1.5 x 2.3 m	4°
Pattern B	20	0.75 x 2.3 m	4°
Pattern C	10	1.5 x 2.3 m	6°
Pattern D	20	0.75 x 2.3 m	6°

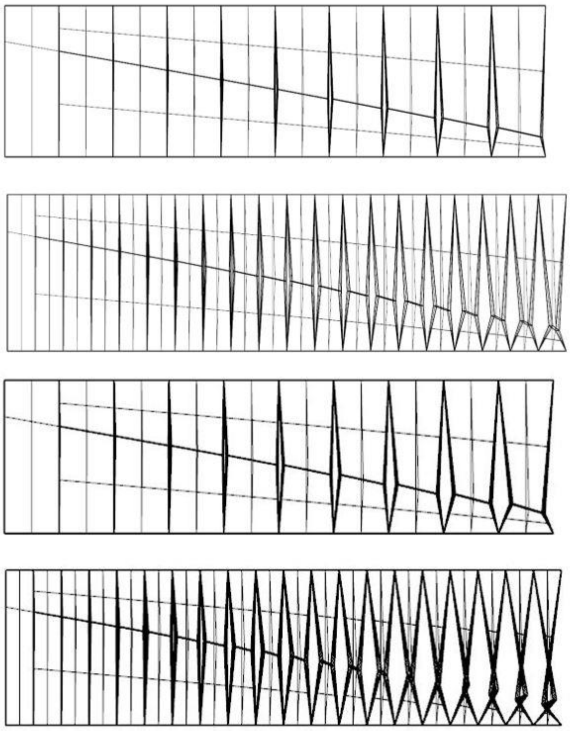

Figure 6. Pattern A, B, C and D.

Energy Simulation:

Energy simulation was run through the ladybug plugin in Grasshopper, Rhinoceros. The process carried out a radiation analysis test on the laboratory model. The analysis aims to estimate the annual indoor radiation of the laboratory for the four different façade iterations. The climate data of Izmir was obtained from Energy-Plus and added to the Grasshopper code. The mesh grid was set for every 20 cm. The code was applied to the original module and then on the four façade patterns; A, B, C and D.

RESULTS

The radiation simulation was conducted on the original model successfully. The mesh grid size was taken for 0.2m x0.2m on all of the energy simulations. The mesh grid created carpet-plots graphs that can be used to determine the optimal configuration. The blue colour represents the lowest radiation levels, and the red colour represents the highest radiation levels. The first aim is to study the solar radiation of each graph and present design feedback on each skin façade iteration potential. The second aim is to identify the most effective skin façade option that fulfils the performance and thermal comfort requirements.

The first simulation results on the original laboratory show that the southern façade receives the highest radiation levels up to 889.62 kWh/m^2 (Figure 7). The variations in this graph are created solely from self-shading, which, compared to the other four charts, provides the highest radiation levels in the southern wing of the laboratory. The lowest radiation levels in

The four patterns A, B, C and D, were applied on the southern façade to test their effect on indoor radiation levels. All four graphs exhibit a noticeable reduction in radiation levels, especially in the southern area of the laboratory. The results of the four optimized patterns displayed a distinct difference from the original model in Figure 7. The lowest radiations in the middle parts reach up to 98.85 kWh/m^2. Figure 8 represents the first façade pattern, Pattern A. This pattern includes wide, almost flat panels with a very concentrated geometry, providing a minimal area for the light to enter the building with its 4° rotation degree. Pattern A records the least amount of red carpet plots among all the graphs, which equals the lowest radiation values admitted into the interior spaces.

Figure 9 presents the second façade pattern, Pattern B. This pattern has narrower panels, with a less concentrated geometry than pattern A. It results in relatively more significant gaps between each panel, providing a wider area for the light to enter indoor. Although pattern A and pattern B possess the same rotation degree, pattern B exposes the interior space to more radiation levels, increasing the red carpet plots in the radiation mesh.

Figure 10 represents the third façade pattern, Pattern C graph. This pattern is similar to pattern A with its wide panels, however, with different rotation degree. The pattern exhibits very concentrated geometry, providing high density in concentration. Though, the gaps in this pattern are wider with 6° rotation degree.

The relatively larger gaps between each panel provide a wider area for the light to enter the building. Therefore, increasing the radiation levels in the interior spaces closer to the southern windows. Although pattern C has a more extensive rotation degree than pattern B, it still provided lower radiation levels in the graph.

Figure 11 represents the radiation values of the fourth façade pattern, Pattern D. The pattern is similar to Pattern B with its narrow panels, however, with different rotation degree. The pattern exhibits low concentration in the geometry, providing wider gaps. The panels in this pattern are with 6° rotation degree.

The relatively more significant gaps between each panel provide more space for the light to enter the building. Therefore, increasing the radiation levels in the interior areas closer to the southern windows. Pattern D has the most extensive rotation degree and the least panel concentration. The radiation graph for pattern D provided the highest radiation levels with the most concentration on red carpet-dot values.

Table 2 categorizes each façade pattern to summarize and compare the characteristics of each façade iteration in accordance with the radiation level results provided by the Energy Simulation.

Table 2. Applied pattern characteristics and radiation levels

Pattern number	No. of panels	Façade panels Rotation	Peak Solar Radiation (kW)	Total radiation reduction %	Reduction per panel (kW)
Original model	0	-	12424	-	-
Pattern A	10	4°	8382	32.52	404
Pattern B	20	4°	8563	31.07	193
Pattern C	10	6°	8490	31.66	393
Pattern D	20	6°	8680	30.13	187

The four façade proposals provided better performance results in the total building peak solar radiation than the original laboratory design. In the results, pattern A provided a 32.52% reduction in the total radiation levels model and 404kWh/m^2 reduction per panel. Pattern B provided up to a 31.07% reduction in total radiation levels and a total of 193.054 kWh/m^2 reduction per panel. Pattern C provided a 31.66% reduction in total radiation levels than the original un-optimized model and 393.377 kWh/m^2 reduction per panel. Pattern D provided a 30.13% reduction in total radiation levels and a total of 187.187 kWh/m^2 reduction per panel. The first pattern, A, provided the best performance and highest reduction of all four designs, while Pattern B provided the best performance per panel between all four panels.

The results confirm that the dimensions and orientation of the panels have an evident influence on the admitted radiation levels into the building. The use of wider panels provides a more concentrated area of solid panels with smaller gaps. Such panels will reduce the admitted light in-between the panels and reduced the radiation levels inside the building. More significant rotation degrees increase the gap ratio between the façade panels, therefore, increases the amount of light admitted. It results in higher radiation levels.

With the reduction of the radiation levels penetrating the façade into the interior spaces, the lower the heat gain will be its better thermal quality. This reduction in the heat gain will reduce total energy consumption in the southern parts of the building to reach thermal comfort for the occupants.

DISCUSSION &CONCLUSIONS

This research encourages the application of double skin façade in Hot-summer Mediterranean climate. The challenges that are faced are summarised because any simulation is prone to error, and any credible verification requires real physical experimentation. Therefore, the process would be time-consuming, especially in the early design stages, where the decisions are required to be taken faster.

The codes provided a real-time analysis that contributes to reducing the gap between qualitative and quantitative radiation performance studies. It studied the solar effect on the different skin facades iteration applied on the same 3D spatial context to produce virtual data visualization of the interior environment, contributing to better-informed design choices.

The research results helped to understand how the DSF overshadows a building and affect the environment and the thermal quality in the interior spaces. According to this study, if the optimum façade size and rotation optimization were integrated with an ecological office building, a wholesome, energy-efficient design would be generated. The facade design alternatives will reduce thermal radiations to a significant rate and indoor environmental quality.

The methodology focused on the investigation of generating 3D parametric skin façade using algorithmic modelling tools. The iteration in the pattern focused on changing the sold to the void ratio by manipulating two rules: sizes of the panel and the panels' rotation. The four different patterns were applied on the southern side of the building, where it receives most sun radiation levels. Environmental performance tools of Ladybug in Rhino, Grasshopper helped to assess the solar radiation levels via Energy-Plus.

This study demonstrates that breaking the repetition in the pattern through the solid-void ratio will significantly affect thermal performance. The results provided up to a 30% reduction in total radiation levels compared to the original un-optimized model. The lowest radiation results were achieved in this study when the façade panels were the narrowest with the minor rotation degree. The study results could not be compared and validated with actual measurements due to covid19 lockdown in the country; however, the method and tools are validated through other studies.

Further studies may explore the underlying mathematical concepts in parametric designs and systematically investigate the architectural fields of varying contemporary sciences parameters. Future researches may explore the digital fabrication, tectonics, and structural performance of the skin façade on different materials while maintaining the same thickness as a constant. The studies may include the various material properties, machine specifications and performance evaluation, then compare and answer various questions related to the skin's formation and appearance, the dimension/size of the skin, and the effect of the investigation on the quality of daylighting and visual comfort.

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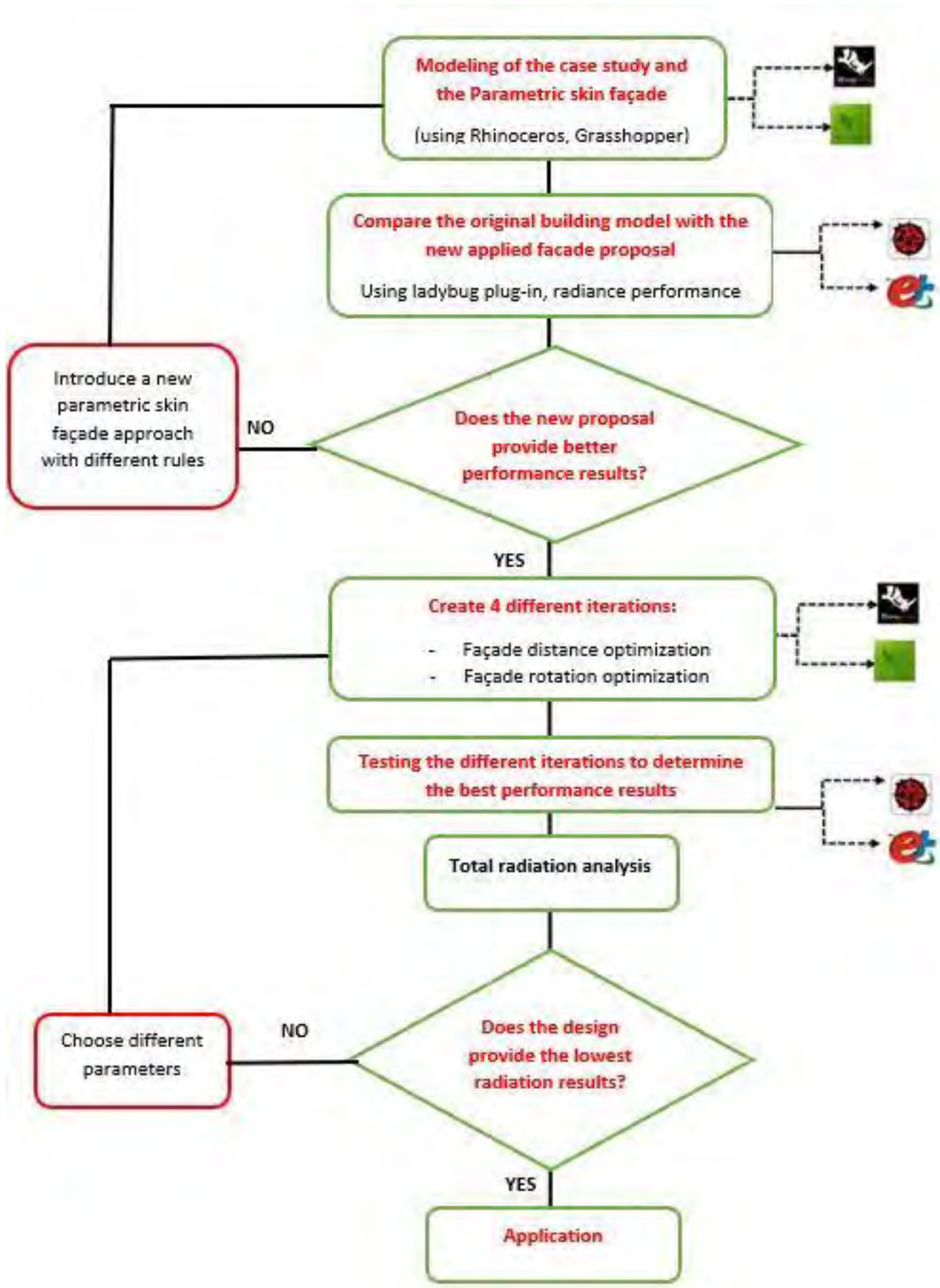

Figure 1: Workflow of radiation analysis in the methodology

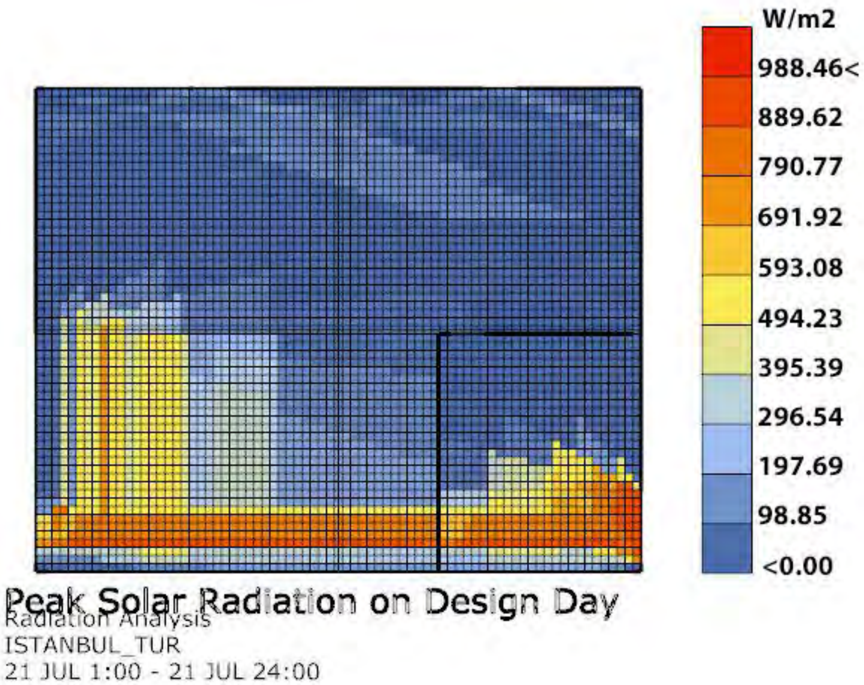

Figure 7: Original model radiation graph values

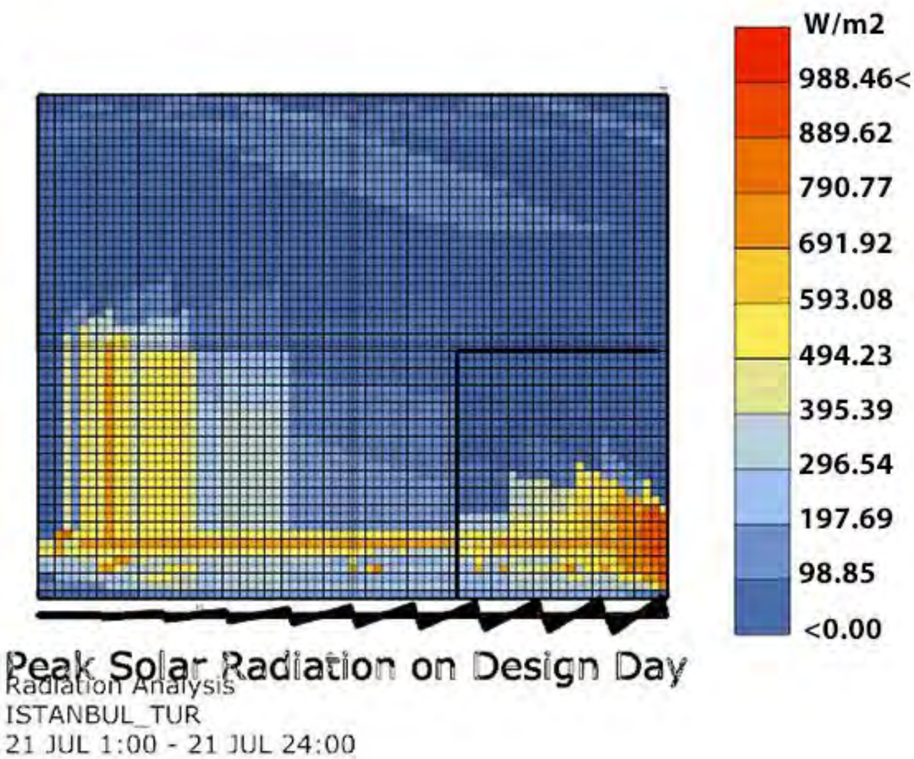

Figure 8: Facade A radiation graph values

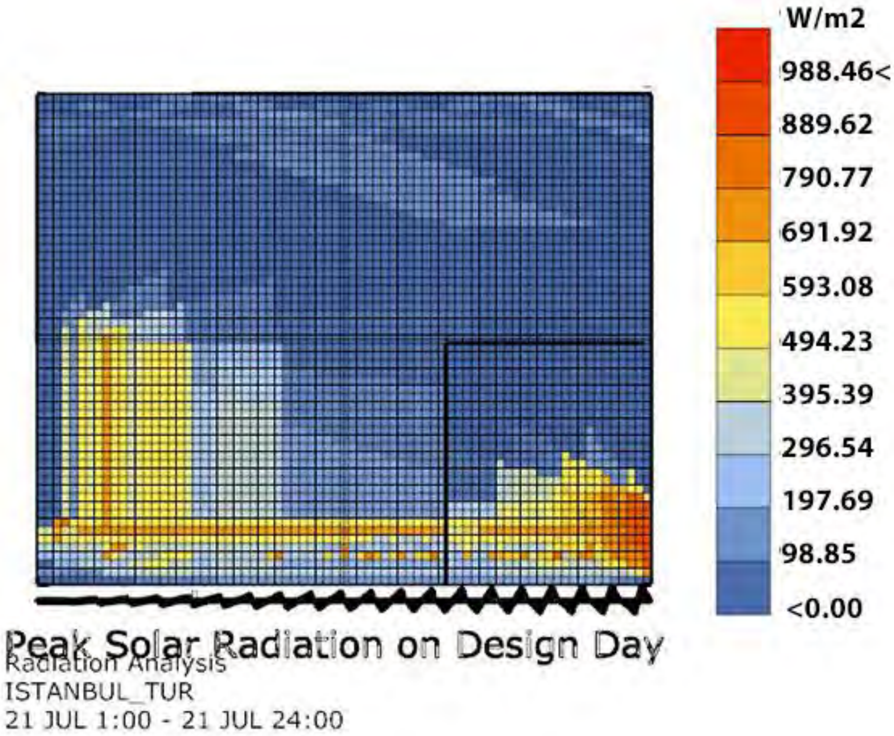

Figure 9: Facade B radiation graph values

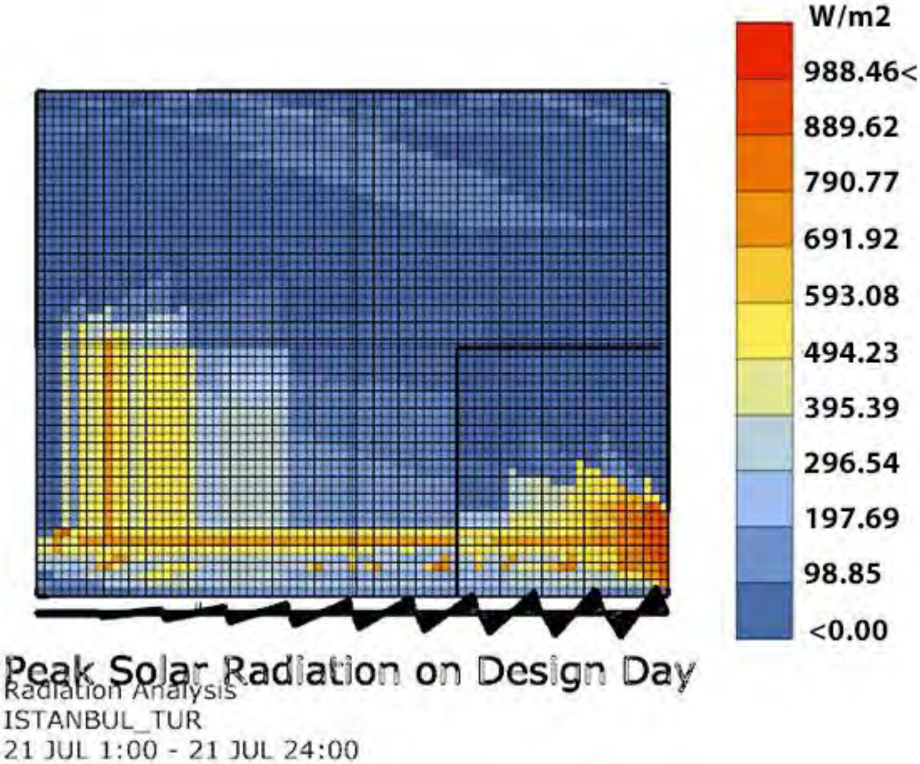

Figure 10: Facade C radiation graph values

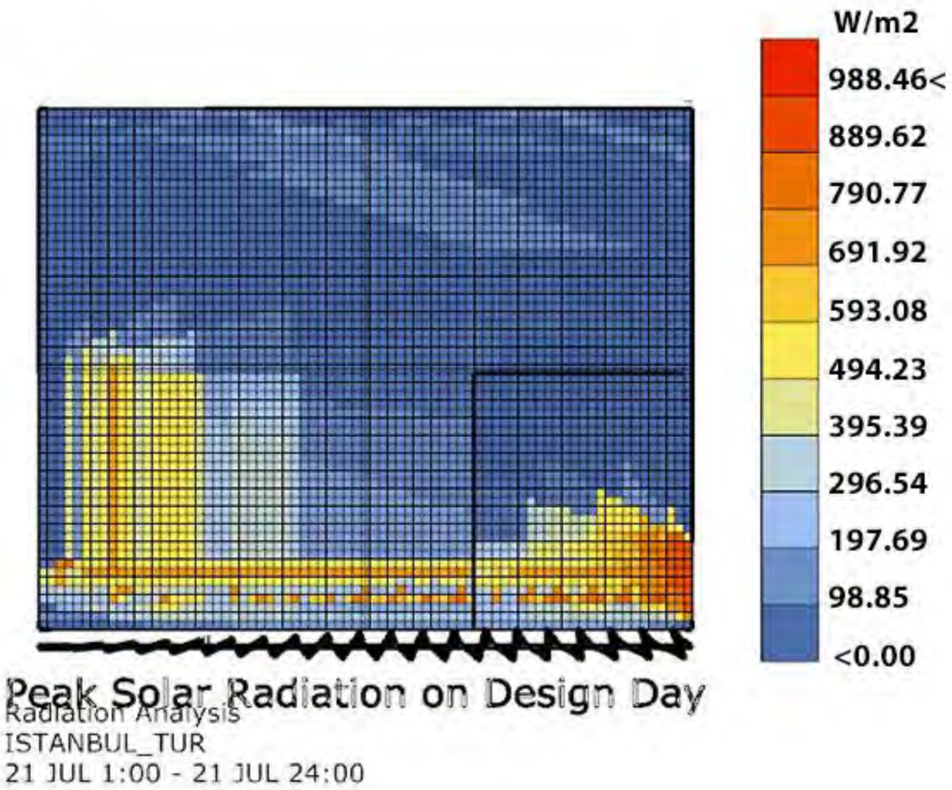

Figure 11: Facade D radiation graph values