Parametric study of expanded metal shading toward Daylight Glare Possibility (DGP) optimization

Rendy Perdana Khidmat1,2*, Hiroatsu Fukuda1, Kustiani3

1 Graduate School of Environmental Engineering, The University of Kitakyushu, 1-1 Hibikino, Kitakyushu, Fukuoka, Japan.
2 Department of Regional and Infrastructure Technology, Institut Teknologi Sumatera, Way Hui, Lampung Selatan, Lampung, Indonesia.
3 Department of Architecture, Faculty of Engineering, Universitas Bandar Lampung, Bandar Lampung, Lampung, Indonesia.

*Email: rendy.perdana@ar.itera.ac.id

Abstract. Patented in the 1880s and having a longstanding industrial history, expanded metal sheet has a remarkable reputation for its application. However, despite the benefits of its use and numerous studies has been conducted on window shading and its daylight evaluation, research on extended metal shading's daylight performance is still limited. This paper investigates the role of expanded metal shading to assess Daylight Glare Possibility (DGP) in Shimonoseki, Yamaguchi, Japan, utilizing parametric design approach and Multi-Objective Optimization (MOO). The simulation and analysis were undertaken to determine how expanded metal can optimize DGP, the significance of improvement, the relationship between the View (aperture) and the DGP, and which parameters have the most influence in driving the aperture size and the DGP value. Analyzing 2322 solutions and 88 Pareto frontiers resulted from the MOO, several findings has been portrayed. Firstly, the shading View (aperture) shows a significant positive correlation to the DGP. Secondly, parameter Strand/W was identified as the most influential parameter that drive the objectives. Thirdly, the validation process portrays optimization in DGP by 38%. The results of the proposed methodology are expected to become an immediate geometry and performance feedback for designers and industries, supporting design decision-making processes during early design phase.

1. Introduction
Contemporary architecture has been tremendously affected by the advancement in architectural computation. Concerning the utilization of computational design, Building Performance Simulation (BPS), helps architecture in predicting the intended building performance in multiple factors such as daylighting, energy consumption, spatial analysis, structural purposes, etc., through simulation. The computer's ability can handle complex mathematical calculations. Thus, the results yielded by the iterative mechanism are possible beyond the designer's imagination. So-called parametric design [1], Considered as defining design using parameters, integrating how the informatics solve the mathematical problem allows the architectural design process to be coupled with design solutions with a high level of complexity and reliability through form-finding or solution generations. The distinguish differences between the classical design process and the parametric
design rely on the taken design step. While the classical design tends to evaluate the design performance once after the first alternative has been completed, the parametric design process is in opposite targeting the intended design performance at the early phase of design and creating the parametric system that driven by a set of parameters as a formulation to produced multiple individuals in which embed performance objectives. Up to this point, it enables higher possibilities to come up with a solution that performs closer to the targeted design performance [2]-[3].

Daylight is coextending built environment and architecture universe. The study on daylighting strategy becomes essential running along with the environmentally friendly architectural design. Considering that people spent most of their time indoor [4]-[5], the provision of daylighting toward window shading and building orientation to support passive design strategy is worthy of being established. The daylight prediction benefits the architect and designer to target comfort and efficiency in several aspects of design. Despite limited and well-documented proof of the link toward human health [6]-[7], daylight is an important factor that may benefiting positively to human health [8] and proving to improve quality works and living environment [9]. What is more, the appropriate strategy of daylighting can reduce energy consumption [10]. To control daylight, numerous strategies has been incorporated. However, the external and internal shading devices still considered as a main feature in responding the constantly changing sky condition [11]-[12]. Shading fenestration functions as a filter to control the daylight and sun radiation before hitting the glazing surface and penetrates the building interior. Thus, by incorporating shading strategy, only the desired and applicable illuminance intensity and targeted sun radiation can enter the working and living space. The objectives of adding shade systems range from aesthetics, cost-effective, sustainability, energy efficiency, productivity and well-being, functional and operational efficiency, comfortable working environment, and security.

Among the system and materials that usually make windows shading, the expanded metal sheet is a favorable modular material with a considerable reputation due to its flexibility and availability. The long reputation brings the material to undergo a long period of standardization, for instance, from the Expanded Metal Manufacturers Association (EMMA) as a National Association of Architectural Metal Manufacturers (NAAMM). The expanded metal is unique due to its characteristics. The material is considered as highly effective efficient materials regarding its manufacture process. Since the material has a long-industrialized market and manufacture, it offers a high level of flexibility in color, patterns, functions, materials, and types. Besides, it is durable [13]. Reusable and recyclable material. What is more, expanded metal has fulfilled at least three critical aspects of the USGBC LEED Green Building rating system’s key areas performance such as Energy and Atmosphere, whereas window shading protects the interior from direct sun, Indoor Environmental Quality in which it provides a connection between outdoor and indoor, and Material and Resources where it contributes to the material waste management system and availability in the local market.

Despite numerous studies in evaluating window shading devices toward daylight performance reveals the benefit of using the computational program to predict and assess daylight objectives, a limited number of the applying computational design processes to study expanded metal as the main shading feature has been done. Given the weather data Shimonoseki, Japan, this research is aimed to test the use of parametric design process and MOO in designing expanded metal shading and optimizing Daylight Glare Possibility (DGP) as one of the daylight metrics to assess visual comfort. Based on the research aims, the objective of the study is to answer the research questions of:

- What is the relationship between the View (aperture) and the DGP based on the MOO results?
- What is the relationship between the expanded metal parameters and the objectives based on the MOO results?
- What is the most influencing parameter toward the DGP and the View (aperture)?

The hypothesis (H₀) of the research is parametric, and MOO can optimize DGP through the iteration (form-findings) of expanded metal shading. While the null hypothesis of this research is the deployment of parametric and MOO has no affect in optimizing DGP performed by expanded metal shading (H₀).
2. Methods

2.1. General insight
This research was conducted in several consecutive steps. Firstly, problem formulation was defined, and daylight metric was decided. Secondly, the baseline and expanded metal model was constructed virtually in Rhino and Grasshopper. In this step, design variable as a dynamic parameters were arranged. Thirdly, the daylight parametric definition was arranged in Ladybug and Honeybee. In this step, weather data and analysis period has been inserted. Fourthly, the MOO processes were run in Octopus. Lastly, after the Octopus produced design solutions from iteration and optimization processes, analysis the DGP, View (aperture), and the tendencies between parameter and objectives was conducted and compared.

2.2. Geometry modelling
The modelling of the geometry encompasses both the baseline model and simulated room equipped with the expanded metal shading. The baseline model is a simulated room without shading, while the main simulated room is the same model equipped with expanded metal shading. The simulated room has been made to represent a standard modular workspace with a single window. Given the sky condition of Shimonoseki, the simulated room is situating following the North-South axis and facing the South orientation with a fixed parameter of 70% of glazing ratio. Besides the glazing ratio, the uncontrollable parameter includes the room height, wide and length. For further result comparison purposes, the baseline model will be equipped with expanded metal geometry in which acting as an outdoor solar protector that furthermore undergoes the overall daylight analysis. The expanded metal geometry was set to run iteration based on the multiple parameters value as number slider input. The dynamic parameters of the shading and the attributes of the geometry are presented in Table 1 and Figure 1.

![Figure 1. The model and the expanded metal shading attributes](image)

| Parameter   | Min  | Max  | Unit | Driven factor | Movement |
|-------------|------|------|------|---------------|----------|
| Height/LW   | 0.05 | 0.2  | cm   | -             | 15       |
| Length/SW   | 1    | 5    | cm   | Height        | 5        |
| Strand/W    | 0.01 | 0.1  | cm   | -             | 10       |
| Bond        | 3    | 10   | cm   | Length        | 8        |
| Angle       | 1    | 9    | °     | -             | 9        |

| Total iteration | 54.000 |

Table 1. Dynamic parameter range value.
2.3. **Daylight simulation**

The daylight simulation targeting DGP value has been proposed incorporating Ladybug and Honeybee [14] that works in Non-uniform Rational Basis Spline (NURBS) based modelling software Rhinoceros and parametric platform Grasshopper. EnergyPlus Weather Data (EPW) set to be December 21 at 12:00 JST was used as a weather data to supply the data that represent the sky condition of the city through the historical weather data observation. The Global Horizontal Illuminance, Diffuse Horizontal Illuminance, and Direct Normal Illuminance, together with the sun position according to certain day in Shimonoseki, are presented in Figure 2. The simulated room and the expanded metal geometry uses the office zone program and Radiance material as adopted in [12], and it is presented in Table 2.

![Daylight simulation](image)

**Figure 2.** Daylight profile and sky condition of Shimonosek.

| Surface       | $\rho$ | $\rho_R$ | $\rho_G$ | $\rho_B$ | Specularity | Roughness |
|---------------|--------|----------|----------|----------|-------------|-----------|
| Ceiling       | 0.800  | 0.800    | 0.800    | 0.800    | 0.000       | 0.000     |
| Interior wall | 0.750  | 0.750    | 0.750    | 0.750    | 0.000       | 0.000     |
| Floor         | 0.210  | 0.210    | 0.200    | 0.200    | 0.000       | 0.000     |
| Glazing $^a$  | 0.750  | 0.750    | 0.750    | 0.750    | 0.000       | 0.000     |
| Shading       | 0.800  | 0.800    | 0.800    | 0.800    | 0.000       | 0.200     |

$^a$ For glazing, the value should be read as transmittance $\tau$

2.4. **Optimization setting**

To collect the assumed best individuals according to the targeted objective value, the MOO uses the expanded metal attributes (Table 1) as an input parameter and the DGP value as well as the View (aperture) percentage as an optimization objective or genome. The optimization engine used was called Octopus [15] given the setting of 0.5 Elitism, 0.2 of mutation probability, 0.9 of mutation rate, 0.8 crossover rate, 100 individual per generation and 200 maximum generation, and using HyPe Reduction ranking method. The target objective is minimum DGP subtraction upon 0.375 the median.
of perceptible glare value range between 0.35 to 0.4, and maximum optical opening of the diamond shaped expanded metal profile.

3. Results and discussion

3.1. Optimization results

Having a perceptible glare as optimization target, the genome was set through minimizing the subtraction factor upon 0.375 DGP value. Due to the time constrain, optimization process was intentionally stopped at generation 47. Up to this point, 2322 solutions and 88 Pareto frontiers solutions has been generated. The distribution of individuals as a design solution categorized by all generations, Pareto frontiers, baseline model and the chosen individuals are displayed in Figure 3.

Analizing the results, it is clear the optimization process was tended to find the solution that has a value distributed along with the axis View (aperture) maximum and DGP minimum. However, related to the targeted value of DGP, only limited Pareto frontier solution included as DGP perceptible glare. In line with this, the majority of Pareto frontier solutions was distributed over the DGP intolerable glare.

![Figure 3](image)

**Figure 3.** The scatter plot of the optimization results.

The distribution of design objective was evenly divided into four DGP category. The perceptible glare was distributed along the View (aperture) axis 40% to 60%, Imperceptible glare below 40%, while disturbing glare occurred when the aperture size over 60%. The coordinate of baseline model and the chosen individual’s coordinate indicate the optimization in terms of DGP. The comparison of the baseline model and the explanation of the chosen individual will be discussed in the other subchapter.

The parallel coordinate plot showing relationship between parameter and objectives in terms of value connection has been displayed in Figure 4. The purple highlighted values along the axis of DGP indicates the individuals in which performs DGP perceptible glare. Confirming the aforementioned relationship between DGP and View (aperture), here the connection of the highlighted wires shows the swarm in View (aperture) ranged from about 40% to about 60%. The connection to the parameter shows rather unclear precedent thus need more closer analysis. The DGP perceptible glare yielded by
the combination of Strand/W 0.03, parameter Bond below 0.3, and Length/LW below 0.9. In term of Hieght/SW, it displays evenly distribution.

![Parallel plot showing connection between parameters and objectives](image1)

**Figure 4.** Parallel plot showing connection between parameters and objectives.

![Correlation between View (aperture) and DGP](image2)

**Figure 5.** Correlation between View (aperture) and DGP.

Figure 5 illustrates the correlation and fit line of the objectives View (aperture) and DGP. Analyzing the scatter plot, the DGP correspond significant positive correlation in relation with the optical opening. Through this correlation value, further analysis using the same sky condition and radiance material can be accurately predicted.

By applying Fitness function calculation to the Pareto frontier, five best solutions have been chosen based on fitness function rank. The solutions attributes are displayed in Table 3 and presented visually both for DGP and expanded metal pattern in Figure 6. From the table, among the best solution, the variation of parameters was still considered lacking. The ratio and multiplication factor between Height/SW and Length/LW shows the same, multiplication factor of 2 for solution rank 1 to 4 and 1 for solution rank 5. Similarly, the parameter Angle shows multiplication factor only 8 and 7, and
Height/SW of more than 0.15 especially 0.16, 0.17 and 0.2, respectively. The table shows the best solution occurred after generation 33,36 generations.

Table 3. Selected solutions based on fitness function values.

| Rank | Model   | Bond | Length/LW | Height/SW | Strand/W | Angle | View | Sub FF | Fitness Function | DGP |
|------|---------|------|-----------|-----------|----------|-------|------|--------|-----------------|-----|
| 1    | 1668    | 0.13 | 0.4       | 0.2       | 0.07     | 40    | 60.48| 0.01964| 105.54          | 0.39|
| 2    | 2237    | 0.11 | 0.34      | 0.17      | 0.06     | 35    | 58.77| 0.01952| 102.23          | 0.39|
| 3    | 2008    | 0.13 | 0.4       | 0.2       | 0.06     | 40    | 64.25| 0.03466| 101.95          | 0.41|
| 4    | 2129    | 0.13 | 0.4       | 0.2       | 0.06     | 35    | 65.56| 0.038297| 101.87         | 0.41|
| 5    | 2139    | 0.05 | 0.16      | 0.16      | 0.07     | 40    | 53.13| 0.005198| 101.60          | 0.38|

Baseline model

| Intolerable glare | Perceptible glare | Perceptible glare | Disturbing glare | Disturbing glare | Perceptible glare |
|-------------------|-------------------|-------------------|------------------|------------------|-------------------|
| No shading        |                   |                   |                  |                  |                   |

Figure 6. Chosen solutions and visualization.

Figure 7. Sensitivity analysis: (a) DGP, (b) View.

To understand and differentiate which parameter has more significant implication toward the movement of objectives value, sensitivity analysis has been conducted by implementing Standardized Regression Coefficient (SRC) to measure the $t$-test. The SRC was run using analysis software JMP utilizing the fit model command in searching the parameter estimate by setting each standardized objectives as role variables and standardized parameter as model effect construction. The sensitivity ranking of the design variables showing the important of each parameter towards the related objective are presented in Figure 7. The positive sign (direct effect) indicates positive relationship and
implication between the parameter to the objective and vice versa (Inverse effect). From the chart, for both objectives, parameter Strand/W, followed by Height and Angle are the most affected parameters driving the value of DGP and View (aperture). However, reverse implication in each objective happens for parameters Angle, Bond and Length/LW.

Figure 8. Box plot showing Strand's role towards objectives: (a) DGP, (b) View (aperture)

The boxplot (Figure 8) portrays the role of parameter Strand/W in driving both the objectives View (aperture) and DGP. Each plot shows similar relationship between parameters and simulation objectives. Analyzing the chart, the variation samples of Strand/W occurred in DGP disturbing glare and View (aperture) between about 56% and 72%. The perceptible DGP has been affected by Strand/W samples ranged between 0.05 to 0.08 concentrated between 0.06 to 0.07, this distribution also responsible for View ranged between 9.39% to 56%, a half of View (aperture) ranged objective values. However, a considerable number of outliers may affect the validity of this section.

3.2. The validation results
To investigate the occurrence and how significant is the optimization toward the two objectives View (aperture) and DGP, the validation analysis needs to be conducted by applying the performance of baseline model and the selected solutions. The comparison between baseline model performance and the best five solutions based on fitness function calculations is displayed in Figure 9.

In terms of DGP, the parametric optimization processes were successfully reducing the DGP value about 0.1 point. However, according to the DGP criteria, none of the best solution performs DGP imperceptible glare. This is probably due to the specific optimization setting, where the target value of the median perceptible glare median has been used. Solution rank 3 and 4 exceed the perceptible glare threshold shows the trade-offs was happening during the iteration process. In terms of View (aperture),
since the baseline model was not equipped with the shading, thus, it is considered performing 100% View (aperture) to the outside, in this condition, no optimization has been made. The trade-offs between objectives yielded the solution with maximum View (aperture) of about 62%, means that the percentage reduced by about 38%.

Considering the research question (sub chapter 1.3), the proposed parametric and optimization platform has been successfully finding the best solution that indicates optimization related to DGP when expanded metal shading is used. Besides, by applying the proposed method, the most significant parameters driving the objectives constant changes has been identified. It is answering the hypothesis (Hₐ) positively and by seeing the results, H₀ is not applicable. The significant of this research is where the relatively popular building material has been investigated deeply. The scope of the investigation was specific includes parameter performance and roles. This study supporting previous research in investigating the role of expanded metal shading [16] toward daylight performance and confirming the expanded metal as an environmentally conscious building material [17]. However, the lack of simulation considered as the limitation of the results. Thus, given the same condition of simulation model and setting, further research is encouraged to run longer simulation.

4. Conclusions
The optimization of DGP was accomplished by the use of parametric and MOO processes in conjunction with expanded metal shading that simulated Shimonoseki's sky condition. The use of the parametric is to be able to iterate design solution rather than to evaluate phase by phase after the design solution is done (classical design processes). The major findings of the research are the occurrence of the best design solutions with its parameters configuration optimizing DGP and the Strand that has been identified as the most influencing parameter driving the optimization objective. What is more, it is found that smaller aperture lead to preferable DGP phenomena. Through this experiment, the decision making related to design process can be supported in relatively less time consuming. Thus, the proposed parametric and MOO processes might well be applied to a broader research of environmentally friendly architecture design and the built environment.

References
[1] Eltaweel A and SU Y 2017 Parametric design and daylighting: A literature review Renew. Sustain. Energy Rev. 73 1086–103
[2] Khidmat R P, Ulum M S and Lestari A D E 2020 Facade Components Optimization of Naturally Ventilated Building in Tropical Climates through Generative Processes. Case study: Sumatera Institute of Technology (ITERA), Lampung, Indonesia IOP Conf. Ser. Earth Environ. Sci. 537
[3] Khidmat R P 2019 Facade components optimization using Generative Algorithm. case study: ITERA, Lampung J. Arsit. Perenc. 2 20–7
[4] Cincinelli A and Martellini T 2017 Indoor air quality and health Int. J. Environ. Res. Public Health 14
[5] Höppe P 2002 Different aspects of assessing indoor and outdoor thermal comfort Energy Build. 34 661–5
[6] Aries M B C, Aarts M P J and Van Hoof J 2015 Daylight and health: A review of the evidence and consequences for the built environment Light. Res. Technol. 47 6–27
[7] Münch M, Wirz-Justice A, Brown S A, Kantermann T, Martiny K, Stefani O, Vetter C, Wright K P, Wulff K and Skene D J 2020 The Role of Daylight for Humans: Gaps in Current Knowledge Clocks & Sleep 2 61–85
[8] Issa M H, Rankin J H, Attalla M and Christian A J 2011 Absenteeism, performance and occupant satisfaction with the indoor environment of green Toronto schools Indoor Built Environ. 20 511–23
[9] Wirz-Justice A, Skene D J and Münch M 2020 The relevance of daylight for humans Biochem.
Pharmacol. 114304

[10] Kaminska A and Ozadowicz A 2018 Lighting control including daylight and energy efficiency improvements analysis Energies 11

[11] Taveres-cachat E, Lobaccaro G, Goia F and Chaudhary G 2019 A methodology to improve the performance of PV integrated shading devices using multi-objective optimization Appl. Energy 247 731–44

[12] Mangkuto R A, Dewi D K, Herwandani A A, Koerniawan M D and Faridah 2019 Design optimisation of internal shading device in multiple scenarios: Case study in Bandung, Indonesia J. Build. Eng. 24 100745

[13] Graciano C, Martinez G and Smith D 2009 Experimental investigation on the axial collapse of expanded metal tubes Thin-Walled Struct. 47 953–61

[14] Roudsari M S and Pak M 2013 Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design Proc. BS 2013 13th Conf. Int. Build. Perform. Simul. Assoc. 3128–35

[15] Vierlinger R 2015 D IPLOMARBEIT Master Thesis Multi Objective Design Interface

[16] Hariyadi A 2017 Study on Side Shading Optimization with Expanded Metal in Kitakyushu 21–4

[17] Darlington A 2014 Expanded Metal Mesh in Architecture