Integrating Computational and Building Performance Simulation Techniques for Optimized Facade Designs

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Abstract. *This paper investigates the integration of Building Performance Simulation (BPS) and optimization tools to provide high performance solutions. An office room in Cairo, Egypt was chosen as a base testing case, where a Genetic Algorithm (GA) was used for optimizing the annual daylighting performance of two parametrically modeled daylighting systems. In the first case, a combination of a redirecting system (light shelf) and shading system (solar screen) was studied. While in the second, a free-form "gills surface" was also optimized to provide acceptable daylighting performance. Results highlight the promising future of using computational techniques along with simulation tools, and provide a methodology for integrating optimization and performance simulation techniques at early design stages.*
Keywords. *High performance facade; daylighting simulation; optimization; form finding; genetic algorithm.*

INTRODUCTION

The building's skin plays the main role in delivering natural daylight to indoor spaces. Performative façade design can significantly improve the indoors visual and thermal conditions, which in turn, improves the quality of life and work environment by creating productive and appropriately lit spaces. Building skins, therefore, shouldn't be just designed for its aesthetic aspects but also as a functioning element in the building.

Building Performance Simulation (BPS) tools are broadly used for achieving designs that have better impact on the users and the environment. While simulation tools are effective in testing and evaluating different designs, it becomes harder when evaluating numerous solutions. Simulation engines usually take a considerable amount of time for each solution. Therefore, it is more practical to consider using optimization tools that can arrive to an optimal solution without the need of testing all possible ones. This paper investigates the ability of integrating computational and simulation tools for design problems with different levels of complexity. The methodology proposed in this research employed a simple Genetic Algorithm for optimizing the daylighting performance of parametrically modeled office building facades.

Genetic Algorithm and Daylighting Performance

A traditional optimization scheme is an algorithm which finds the minima or the maxima of a given function, typically known as the objective function. The objective function may depend on any number of parameters and any combination of parameter values within the defined search space is considered a feasible solution. The optimal solution will be the feasible set of parameters which minimizes (or maximizes) the objective function. A problem will not necessarily have one unique solution. It may have no optimal solutions at all, a finite number of solutions, or an infinite number of solutions, which can be defined as a more specific subset of the search space (Papalambros and Wild, 2000). For problems which involve simulation engines heuristic search algorithms are usually used and considered an appropriate choice. These algorithms are considered heuristic as they depend on trial-and-error approach and as such, they are not guaranteed to converge to true optimal solutions. However, most of these algorithms do find solutions which are very close to optimal (Gagne and Anderson, 2010).

The Genetic Algorithm (GA) is an algorithm which works by mimicking the process of natural evolution and was first introduced by Holland and Reitman (1977). It is one of the most commonly used heuristic search techniques, and has been applied to many types of architectural problems. Genetic algorithms had been successfully used in several research works for enhancing daylighting performance. Tsangrassoulis et al. (2003) presents a technique for the design of slat-type blinds based on the relative light intensity distribution under a uniform light source. The technique used a genetic algorithm in order to evolve the design according to a set of parameters. Another research investigated altering free-form ceiling geometry design to optimize indoor daylight uniformity ratios (Rakha and Nassar, 2011). Other research works focused on optimizing the facade design and openings to achieve better daylighting levels and comfort (Torres and Sakamoto, 2007; Gagne and Andersen, 2010; Portugal and Guedes 2012).

Although several investigations had been previously carried out on using genetic algorithms for performance optimization, most of the previous researches were made on simplified problems, such as window positions or shading device parameters. This paper aims to investigate the proposed methodology under two conditions. A simplified guided-search case, where several cases and parameters that are predicted to offer good results are being optimized. The aim in this case is to find a better solution from numerous good solutions, in other words an optimal solution. Conversely, the second case investigates an exploratory search that has no guides to start with. A free form façade design was optimized for better daylighting performance. A larger number of choices and parameters were also introduced in order to investigate the methodology's ability in problems with a larger pool of solutions. The aim of the second case is not mainly reaching an optimal design but instead to discover the potential of using the proposed methodology in more complex contexts.

METHODOLOGY

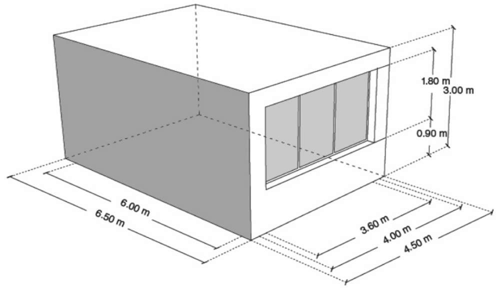
A typical side-lit office room space was selected for investigation. The case study was chosen to be located in the city of Cairo, Egypt (30° N- 31° E). The office is room is a 4.00m wide by 6.00m deep rectangular space, with 3.00 m clear height. The office space was assumed to have a 6 mm double glazed window that is 3.60m wide and 1.80m high (Figure 1 and Table 1). The space was considered to be on ground level with a free horizon and no obstructions. Ground reflectance of 20% was assumed. At first, the base case was modeled and its annual daylighting performance was observed. Afterwards, Genetic Algorithm (GA) was used for optimizing the annual daylighting performance of two parametrically modeled cases. In the first case, a combination of a redirecting system (light shelf) and shading system (solar screen) was added to the base case. While in the second, a free-form "gills surface" façade was also optimized to provide acceptable daylighting performance.

Daylighting Simulation Methodology

Simulation was conducted using the Diva-for-Rhino V 2.0, a plug-in for Rhinoceros modeling software. It was used to interface Radiance and Daysim for annual simulation and illuminance computation (Reinhart et al., 2011). Simulation was conducted annually for weekdays from 8:00 AM to 4:00 PM which represents a typical Egyptian eight-hour working

Figure 1
Isometric view of the studied office room.

Table 1
Dimensions and properties of the tested office space.



Space Dimensions and Materials		
Floor level		Zero level
Space dimensions (m)		4.00 * 6.00 * 3.00
Walls	Reflectance	50%
	Material	Medium Colored
Ceiling	Reflectance	80%
	Material	White Colored
Floor	Reflectance	20%
	Material	Wooden Floor
Window Dimensions and Material		
Width (m)		3.60
Sill (m)		0.90
Lintel (m)		2.70
Glazing		Double clear glass 6 mm (VT = 0.647)

time. The reference plane on which daylight performance was simulated contained 117 measuring points in a grid of 0.5m* 0.5m, at a working plane of height 0.8 m. Measurements that were found equal or higher than the recommended minimum illuminance value for an office space, 500 Lx, were considered "adequate" (IESNA, 2000). Daylight Availability a Dynamic Daylight Performance Metric (DDPM) was used for evaluation. It presents three evaluation criteria: "daylit" areas (the adequate areas), for spaces that receive at least half the time sufficient daylight compared to an outside point, "partially daylit" areas, which are below useful illuminance and "over lit" areas that provide warning when an oversupply of daylight (10 times target illuminance) is reached for at least 5% of the working year. Analysis criteria for Daylight Availability adopted in this paper assumed that the designs that achieved equal or more than 50% "daylit" areas and at the same time minimum values for "over lit" and "partially daylit" areas were considered efficient.

Parametric Modeling and Optimization Methodology

Generative designs and parametric models were modeled using Grasshopper a plug-in for Rhinoceros modeling software. Grasshopper allows changing the model parametrically where each design parameter is directly linked to a floating-point slider that determines its value. Galapagos, an evolutionary solver, is a GA optimization tool used within the platform of grasshopper and was used to control and modify the different parameters. During the GA process, a set of initial solutions (a generation/population) is generated at random. Each solution is sent to DIVA for conducting Daylight Availability simulations. The results are then processed to calculate the daylit area percentage using a fitness function that is expressed as:

$$F(x) = N' / N \quad (1)$$

where N is the total number of measuring nodes, and N' is the number of nodes which receive at least half the time sufficient daylight.

Solutions that result in good performance are used as "parents" for a new generation. Parent members are combined using a genetic operator called crossover to create a new generation of "child" members which have characteristics of the parents. Since this new generation is based on the best performing solutions in the previous solutions, it is assumed that some members of the new generation will perform better. Once evaluated, again the good performers are used as parents while the poor performers are discarded. The cycle continues until a number of generations have been completed. In this research a simple GA with 20 genome/generation was used. Optimization continues until an optimal solution is obtained and remained unsurpassed for continuing twenty generations (Stagnant Generations) (Figure 2).

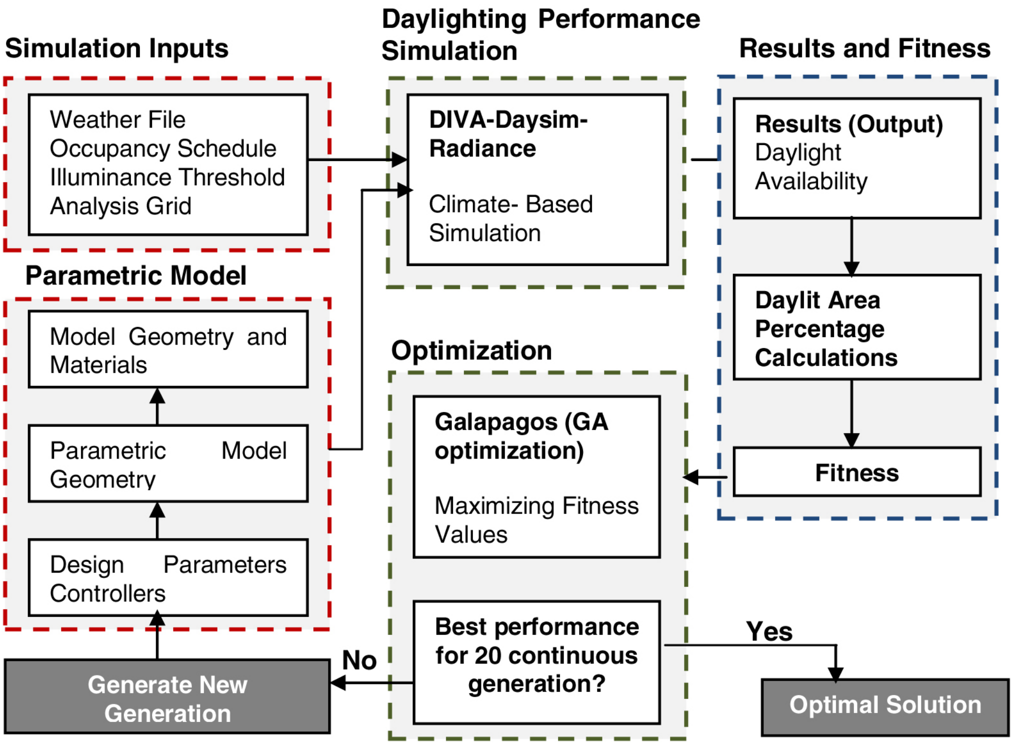


Figure 2
Optimization methodology diagram.

BASE CASE SIMULATION RESULTS

Daylight availability was analyzed for the base case facing the South and the East orientations. Both South and East facing spaces were subject to the penetration of the direct sun. Overlit areas reached 43% in the South and 42% in the East. However, no partially daylit areas were anticipated in South oriented office space where daylight area reached 53%. In the East faced room, 13% of the space were found to be partially daylit (Table 2). The main challenge, therefore, is to eliminate the overlit areas without a significant increase in partially daylit areas.

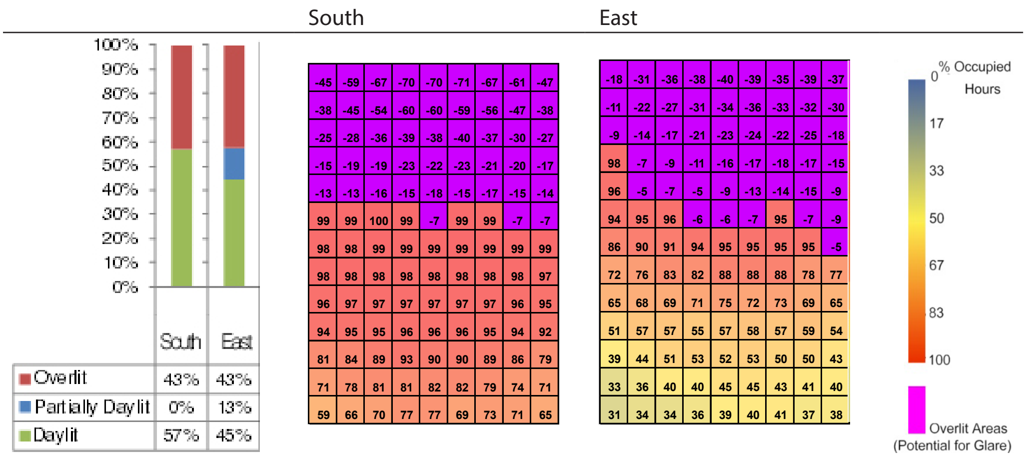
FIRST CASE STUDY: LIGHT SHELF AND SOLAR SCREEN COMBINATION

In previous research work by Sherif et al. (2012), solar screens were found to be highly effective in eliminating the overlit areas. However, in many cases that came with a drawback in the overall performance due to the increase in partially daylit areas. Combining the solar screen with light shelves was found to achieve better results. In this case combining solar screens and light shelves was examined. The design parameters of both systems change according to the results obtained from previous research works (Sabry et al., 2012). The parametrically modeled cases had six different changeable parameters shown in Table 3. Overall, the number of resulting possible designs exceeds two thousand possible solutions.

Daylighting performance optimization results

An optimal design was obtained and the performance reached 64% in the sixth generation, where

Table 2
Daylight availability distribution for the base case in South and East orientations .



a 1:1 (H: V) screen with 90% perforation and 50° VSA was combined with a 120 cm, 10° rotated light shelf. It remained the best solution for the next twenty generations. However, several designs also went far beyond the performance of the base case (45% daylit area). Moreover, all the proposed solutions had minimal overlit area percentages which didn't exceed 7% of the whole space area and several cases succeeded in entirely eliminating the overlit area. Figure 3 shows the simulation results after the 26 generations. It's noticed that the optimal solution was reached at an early stage within the first six generations. The process afterwards wasn't successful as the coupling with new solutions resulted in worse solutions while the optimal solutions kept unmatched. Table 4 illustrates the best results obtained from the optimization process.

SECOND CASE STUDY: FORM FINDING

Form-finding can be described as a process of discovery and editing (form emerges from analysis). Extreme form-finding is not fully architecture but more applied engineering as form exclusively determined by function. In this case study a free form daylighting system was proposed. Similar to the previous studied case, this system combines a redirecting and shading techniques, however the form is more organic and fixable. A "gills surface" was modified to be used as a shading devise in the lower part of the window and as a light shelf in the upper part. Gills

Table 3
Parameters considered for the first case.

Solar Screens

Parameter	Possible values
Vertical Shading Angle (VSA)	70°, 60°, 50°, and 40°
Perforation	90%, 80% and 70%
Aspect ratio (Horizontal: Vertical)	1:1, 2:1, and 4:1

Light Shelves

Parameter	Possible values
External light shelf depth	60 cm, 80 cm, 100 cm, 120 cm
Internal light shelf depth	30 cm, 60 cm, 80 cm
External light shelf rotation angle	0°, 10°, 20°, and 30°

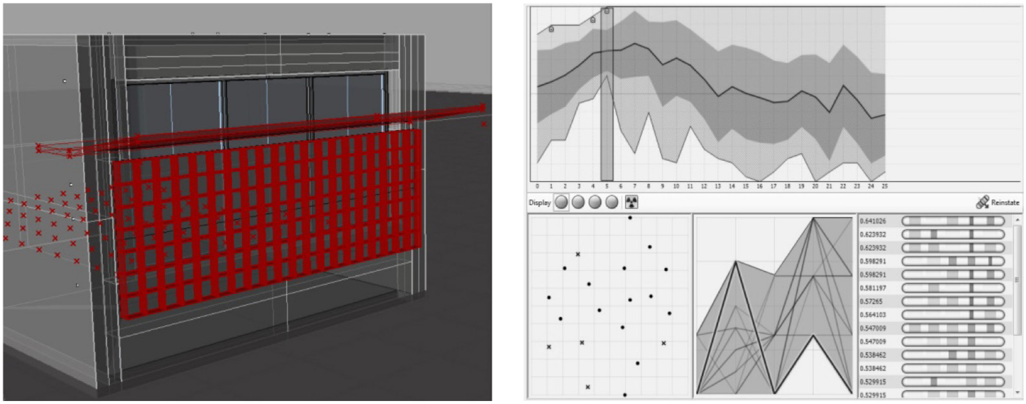
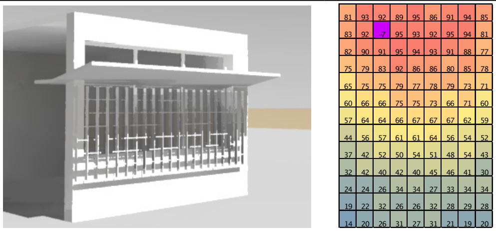


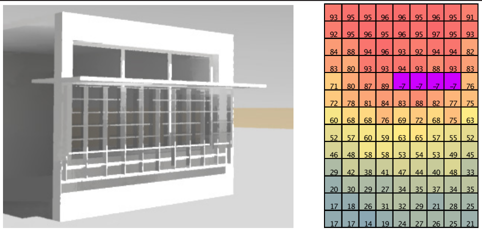
Figure 3
First case study after 26 generations, fittest design had 64% daylit area.

Table 4
Cases with highest performance for the first case study. It's noticeable the diversity in the solutions and the relatively small overlit area percentages.



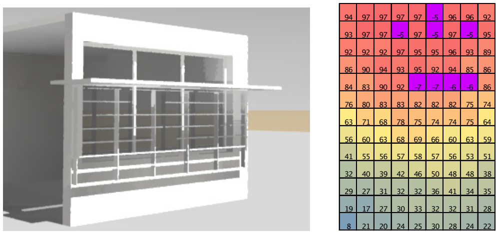
Screen configurations: 90%, 1:1, 40°
Light shelf configurations: Ext. 100 cm. 10°, 60 cm Int.

Daylit	64%
Overlit	0%
Partially Daylit	36%



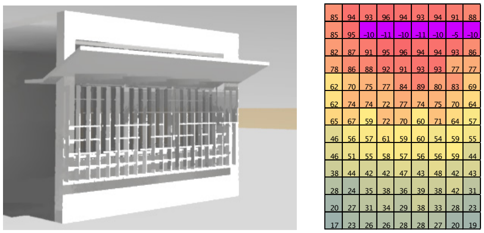
Screen configurations: 90%, 2:1, 50°
Light shelf configurations: Ext. 100 cm. 0°, 60 cm Int.

Daylit	62%
Overlit	3%
Partially Daylit	35%



Screen configurations: 90%, 4:1, 40°
Light shelf configurations: Ext. 100 cm. 0°, No Int.

Daylit	62%
Overlit	7%
Partially Daylit	31%



Screen configurations: 80%, 1:1, 40°
Light shelf configurations: Ext. 120 cm. 20°, 60 cm Int.

Daylit	61%
Overlit	6%
Partially Daylit	33%

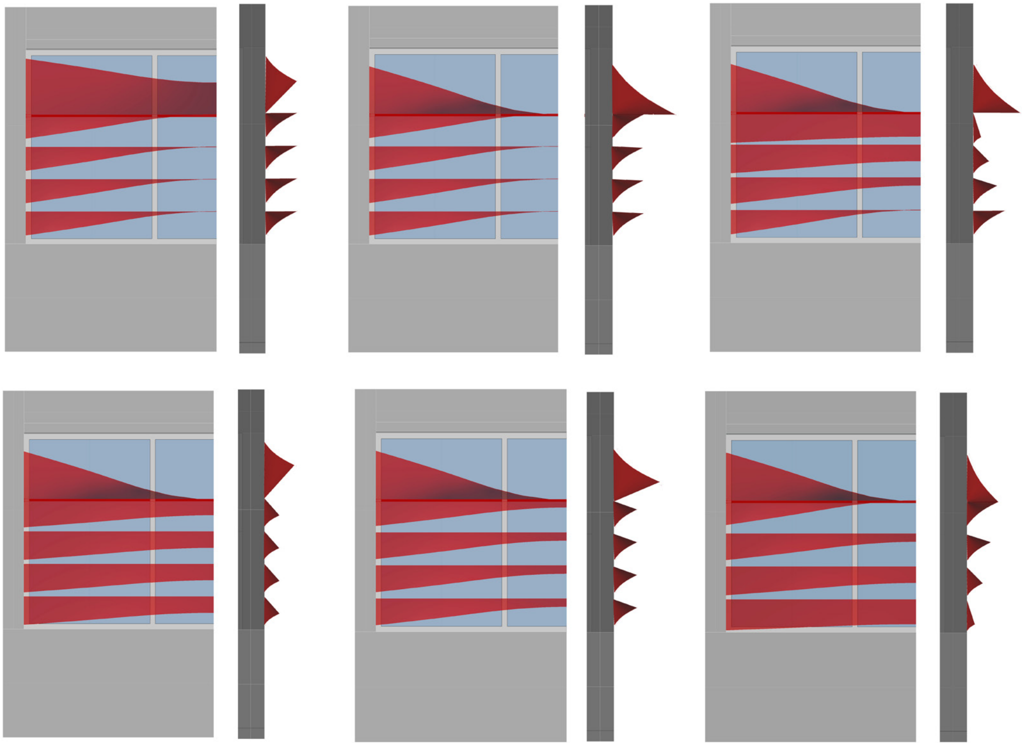


Figure 4
ifferent shapes and settings for the façade of the second case study.

surface is a free form inspired from nature and has been recently used in several architecture works.

The proposed system was applied to the South facade and was parametrically controlled to provide a wide range of options. Every louver had a median control point which represents the curve peak. This point has the ability to move in the vertical and horizontal direction to control the openness and closeness of that part as well as the amount of shading it provides. The transition of the rest curve points is, however, not unique; Instead it follows a *Gaussian* curve were transition is defined by a symmetrical sequence of values, with null extremes. Similarly, the curved light shelf in the upper part has a similar point that controls its extension and curvature. Sixteen positions are optional for each single part of the system and more than two millions different designs are obtainable. Such a huge pool of design choices highlights the necessity of using tools such as genetic algorithms for finding designs that can provide suitable performance (exploratory analysis). Figure 4 shows different shapes and settings for the façade.

Daylighting performance optimization results

The algorithm succeeded in providing several acceptable cases considering the fact that the designs were found to have a wide range of performance (oscillated from 56% high to as low as only 5%). It might be useful to use such a tool to limit the options in the beginning of the design phase. An optimal solution was obtained in the second generation and continues to be the fittest for the remaining

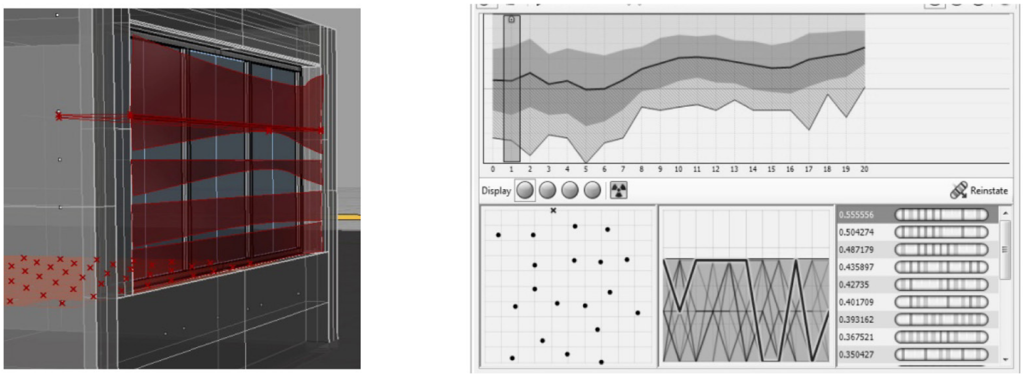


Figure 5
Second case study after 21 generations, fittest design had 56% daylit area.

twenty generations. The optimal solution had 56% daylit area. Results show that the algorithm wasn't able to conduct a real optimization, most likely because of the extremely wide solution space and the simple characteristic of the algorithm. Larger generations and more computing time (more generations) would have possibly reached better results. However, it's hard to judge the success of the algorithm without further optimizations. Figure 5 shows the optimization progress and Table 5 shows the best performing cases.

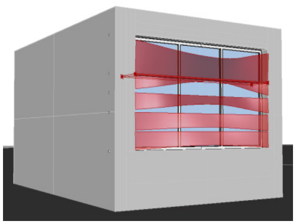
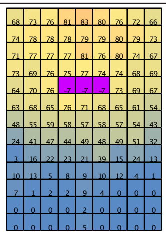
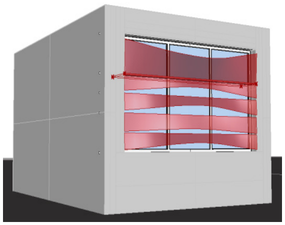
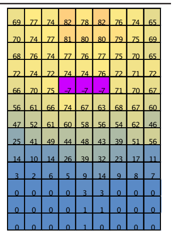
CONCLUSION

The two studied cases demonstrated the ability of the Genetic Algorithm in producing designs with acceptable daylight performance. However, the performance of the optimization tool was found to differ based on the complexity of the problem. In the first case, The GA reached a near optimum solution and succeeded in reaching solutions that have a significantly better performance compared to the base case. It's, therefore, recommended to use optimization tools and evolutionary solving methods in guided searches for optimal solution from various possible options.

In the second case, and because of the vast number of solutions, the algorithm seemed to settle with a local optimal. Although, it may be hard to judge the results unless more optimization trials with different setting are made, the algorithm was found to be a suitable exploratory method to limit the options when no previous experience is available. This is an exceptionally useful feature that enables the integration of performance analysis in earlier stages of design.

The proposed methodology can be adjusted to

Table 5
Cases with highest performance for the second case study.

			
Daylit	56%	Daylit	53%
Overlit	2%	Overlit	3%
Partially Daylit	42%	Partially Daylit	44%

diverse contexts and objectives. Form generation and form finding using evolutionary solvers can open the door for more performative designs with unlimited creativity and minimum restrains. The proposed methodology can also aid architects in taking design decisions in the early design stages.

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