Multi-Objective Performance Evaluation of Adaptive Façade in Hot Arid Climate

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Abstract

A drift from complex and energy-intensive systems for adaptive facades towards material-based actuation systems started to take place in the recent past. The adaptability limitations of these newly proposed passive architectural applications question the capacities and performative potentials of material-based actuated facades. Limited investigations were carried out to tailor material-based façade systems to desired performative objectives, and were generally dictated by one sole material property. This study examines the performance and functional necessity of more diversified responses for material-based adaptive systems, based on a case study of a shape memory alloy actuated adaptive component under Cairo-Egypt climate. The building performance goals were set to reduce incident solar radiation, improve interior daylighting, and increase visual connectivity to the outside; and were evaluated based on exhaustive parametric simulations running on Radiance engine. The research findings suggest that the larger geometrical repertoire, adaptability, and façade layering allow the passive adaptive system to reach its higher performative potentials for which improvements can reach up to 125% from a similar one-layered static facade.

Introduction

Adaptive architectural technologies were intensively investigated in the recent past to improve building performance through controlling energy flows. However, their development was restrained due to their electromechanical complexity, high-energy consumption, and high cost. This shifted interest to material-based actuation for adaptability in dynamic facades. (Kolarevic, 2015; Kolarevic and Parlac, 2015; Speck et al., 2015)

Generative material approaches in architecture are not conceptually novel, while their application in dynamic rather than static architecture can be considered state-of-the-art. The HygroScope and HygroSkin projects[1], for instance, utilized the property of wood to oscillate between attracting and evaporating water molecules from its environment, a characteristic usually considered a material deficiency, to derive the opening and closing of apertures (Menges and Reinchert, 2015). Other biomimetic approaches included the work of Doris Sung in Los Angeles where bimetallic panels[2], bending at direct sunlight exposure within a canopy structure, were used to improve ventilation through aperture openings for hot air escape (Kolarevic and Parlac, 2015). The Living Glass prototype by Benjamin and Yang, Shape-Shift by ETH Zurich, the Air Flower by Lift Architects and many others employed shape-memory materials, alloys or polymers[3] for the actuation of their prototypes, while relying for the majority on heating through electric current in contrast to solar radiation by a few (Parlac, 2015).

The attribute that all these examples have in common is a systemic simplicity reliant entirely on material properties for sensing and actuating. While the environmental performance criteria were the basis for most of their geometry and mechanism design concepts, a critical evaluation and integration of the performative impact on the selected criteria for each was rarely carried out for adaptive material-based facades, and the conclusions were based on the premises of logical interactions.

Among the exceptions to that is the Adaptive Skins project (Verma and Devadass, 2013), a project that uses shape memory alloys (SMAs) for actuation of tensegrity modules. The project interestingly integrated between design and performance evaluation both as a generative tool and a feedback tool. A genetic algorithm was used to optimize the designed system, where the gene input was the three actuation types, each within their range of actuation, while the fitness function was based on weighted combination of exposure analysis and incident radiation (Verma and Devadass, 2013). A seasonal-differentiating function was developed for a minimum angle of incidence in winter, and minimum solar exposure in summer and vice-versa (Verma and Devadass, 2013). A post-design evaluation of daylight and direct solar exposure showed a quantifiable improvement: a 70% decrease in direct solar exposure and resultant daylight levels of about 1800 lux (Verma and Devadass, 2013). Although this generative method provided a means for more appropriated solutions for the desired environmental objectives, the general resulting outputs of such systems are limited to binary outputs and are a compromise combined benefit rather than tailored responses for specific climatic needs.

[1] Projects developed by Achim Menges's Institute of Computational Design at the University of Stuttgart, with a meteorosensitive morphology where wood responds to the weather changes with a humidity-based motion (Menges and Reinchert, 2015).

[2] Two laminated sheets of metals with different thermal expansion rates.

[3] Materials which deform and recover by temperature changes.

Methodology

The objective of this study is to examine the performance and functional necessity of more diversified responses for material-based adaptive systems. Based on a shape memory alloy actuated adaptive façade design developed in a previous study (Mokhtar, 2016), the evaluation of alternatives was carried out. Two main variables are investigated for improved performance: partitioning a façade’s geometrical composition and adding the adaptability dimension to the design. A detailed implementation process and strategy for the study follows identifying context, adaptive shading structure, evaluation criteria, and simulation environment.

Case Study Context

A generic south-sided day-lit office space, located in Cairo-Egypt, was used for this assessment, with spatial dimensions of 4 by 6 meters, assuming no obstructions, illustrated in Figure 1.

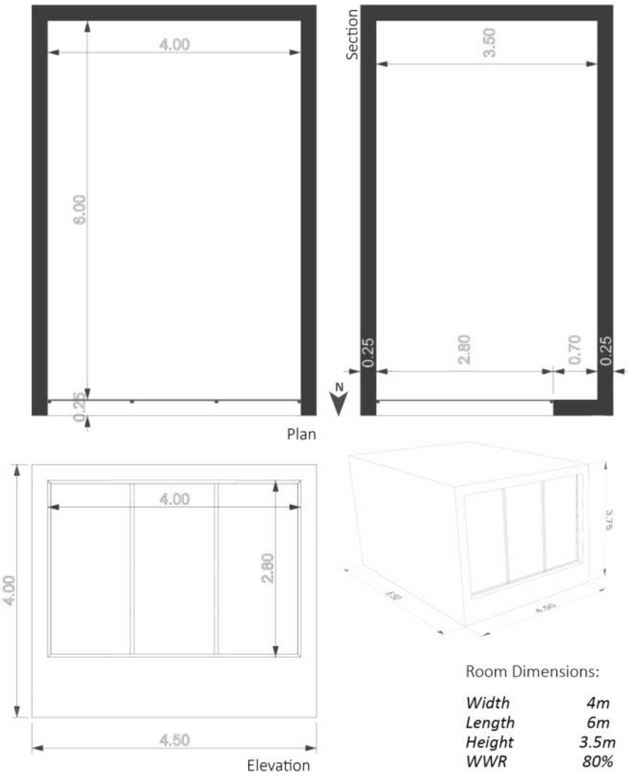

Figure 1: Spatial Characteristics of Modelled Space for Performance Evaluation

The evaluation was performed through digital modelling and simulation, with specifications detailed in Table 1.

Table 1: Digital Modelling Parameters and Evaluation Period

Modelling Environment		Rhino 3D modelling software along with its parametric plugin Grasshopper
Material Reflectance	Walls	50%
	Ceiling	80%
	Floor	20%
	Window VT	80%
Window-to-Wall Ratio		80% ($11.2m^2$)
Building-Shading Gap		100mm
Evaluation Period		Hourly from 08:00 to 17:00 on the 21st of March, June, September, and December

Adaptive Shading Structure

An origami-based geometry, designed in a previous study, producing several shading forms and actuated by 4 shape memory alloys located on the four corners of the shading panel, is investigated. These forms include nine which are specifically explored and are illustrated in Figure 2 below.

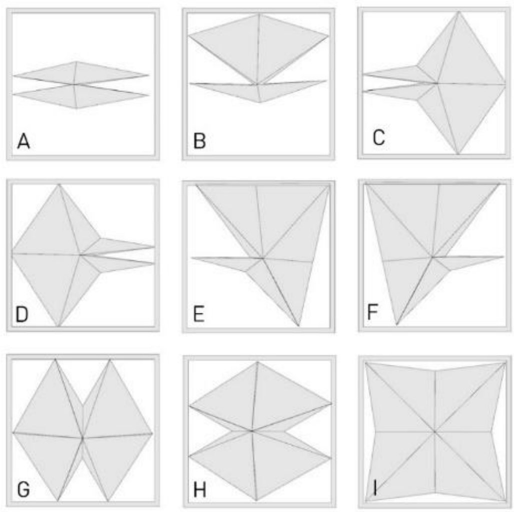

Figure 2: Nine Investigated Geometries (Mokhtar, 2016)

A shading grid of 9 by 6 is used to accommodate for the 400mm square panel shading design, shown in Figure 3. The nine form alternatives developed by the component geometry design were used in two different systems. The first system used one identical component for the whole façade, while the second divided the façade into two portions hence two different component geometries. The latter was investigated to identify the degree of functional variability needed within the same orientation. This necessary variation is based on the relevance of the middle part of the facade to the anthropomorphic scale and openness to the outside, in contrast to the upper portion which is only impacted by environmental needs. The incorporation of that façade portioning dimension created a set of 81 combinations to be evaluated, which is based on the possibility of nine different ones for each portion.

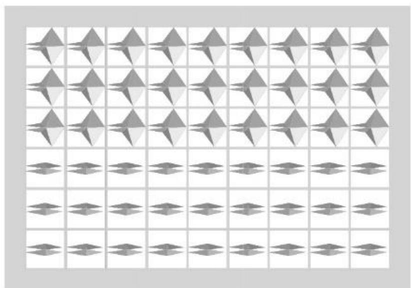

Figure 3: Façade Shading Grid and Layering (Mokhtar, 2016)

Performance Evaluation Criteria

A performance evaluation framework was developed for the adaptive facades based on the three considered environmental design objectives of reduced solar radiation, improved daylighting and increased visual fields to the outside. The evaluation characteristics for each of the three objectives were defined based on adaptations of industry standards, (IES Daylight Metrics Committee, 2012; Mardaljevic, 1998; Reinhart and Wienold, 2011), for which the detailed parameters and variables are outlined in the Table 2.

Table 2: Evaluation Methods and Parameters

	Solar Radiation	**Daylighting**	**Openness**
Measure Variable	Hourly Incident Solar Radiation	Hourly Illuminance	Portion of shading geometry that is open
Unit	$W \cdot m^{-2}$	lux	%
Metric(s)	Hourly incident solar radiation on the building surface	*Useful Daylight Illuminance:* Percentage of room receiving sufficient daylight at least 300lux, and lower than the glare threshold, identified as 2,000lux.	Percentage of open area in the shaded façade in the heights relevant to visual connectivity
Simulation Tool	Radiance engine through Ladybug[4]	Radiance engine through DIVA[5] for Grasshopper	
Analysis Grid	10 by 10mm on the building surface	300mm by 300mm, 800mm above ground	
Simulation Parameters		Ambient bounces: 6, divisions: 4096, sampling: 1024, accuracy: 0.1, resolution: 512, Direct Threshold: 0.	
Reference		(IES Daylight Metrics Committee, 2012; Mardaljevic, 1998; Reinhart and Wienold, 2011)	

Performance Improvement Strategy

An exhaustive method, simulating the 81 cases, was used to evaluate the three criteria individually. The configurations achieving the highest performative values for each objective helped inform the necessary underlying design logic. A multi-objective approach to the evaluation of alternatives was achieved through an exhaustive search against the three objectives, and the choice of the most performative cases was based on the comparative weight of the three objectives.

Performance Evaluation

The useful daylight illuminance and average incident radiation for each case, for the 40-hour set of a year's representative sample, were evaluated, and enlisted in *Figure 5* and *Figure 6* respectively. Figure 4represents a sample of nine cases for June. The horizontal hierarchal structure indicates, on the outer larger side, the form on the upper façade portion (UFP) with a sub-structure that indicates the form on the lower façade portion (LFP). This representation is a visual mapping of the connection between geometrical combinations, time, and performative quality.

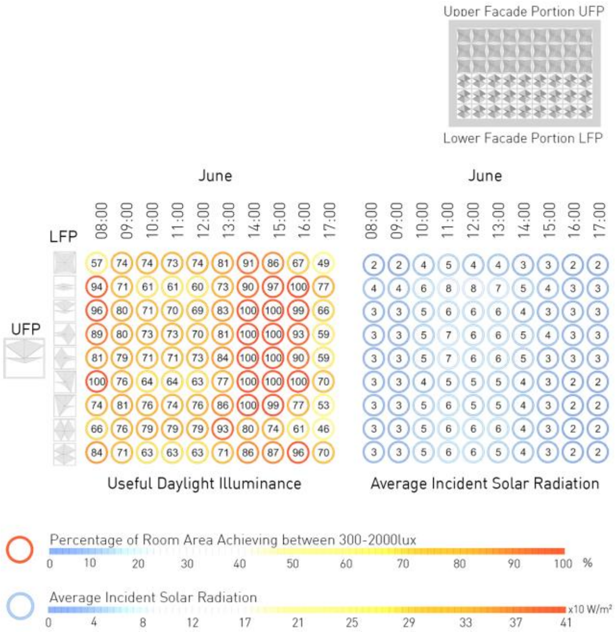

Figure 4: Illuminance and Radiation Values for Sample Configuration in June

The minimum recommended requirement for useful daylight of about 75% was observed to be mostly unachievable in all case using static shading geometry throughout the year. Additionally, the values for lowest solar radiation, except for the completely closed configuration, did not weigh towards one single formal representation. This further strengthens the argument for a variation of geometries based on their time-dependent efficiencies.

[4] Ladybug is an open source plugin that help evaluate and visualize environmental performance using imported data from EnergyPlus weather files (Roudsari and Pak, 2013)

[5] DIVA-for-Grasshopper is a plugin for daylighting optimization and energy modelling, through linking models to Radiance engine ("DIVA for Rhino," n.d.)

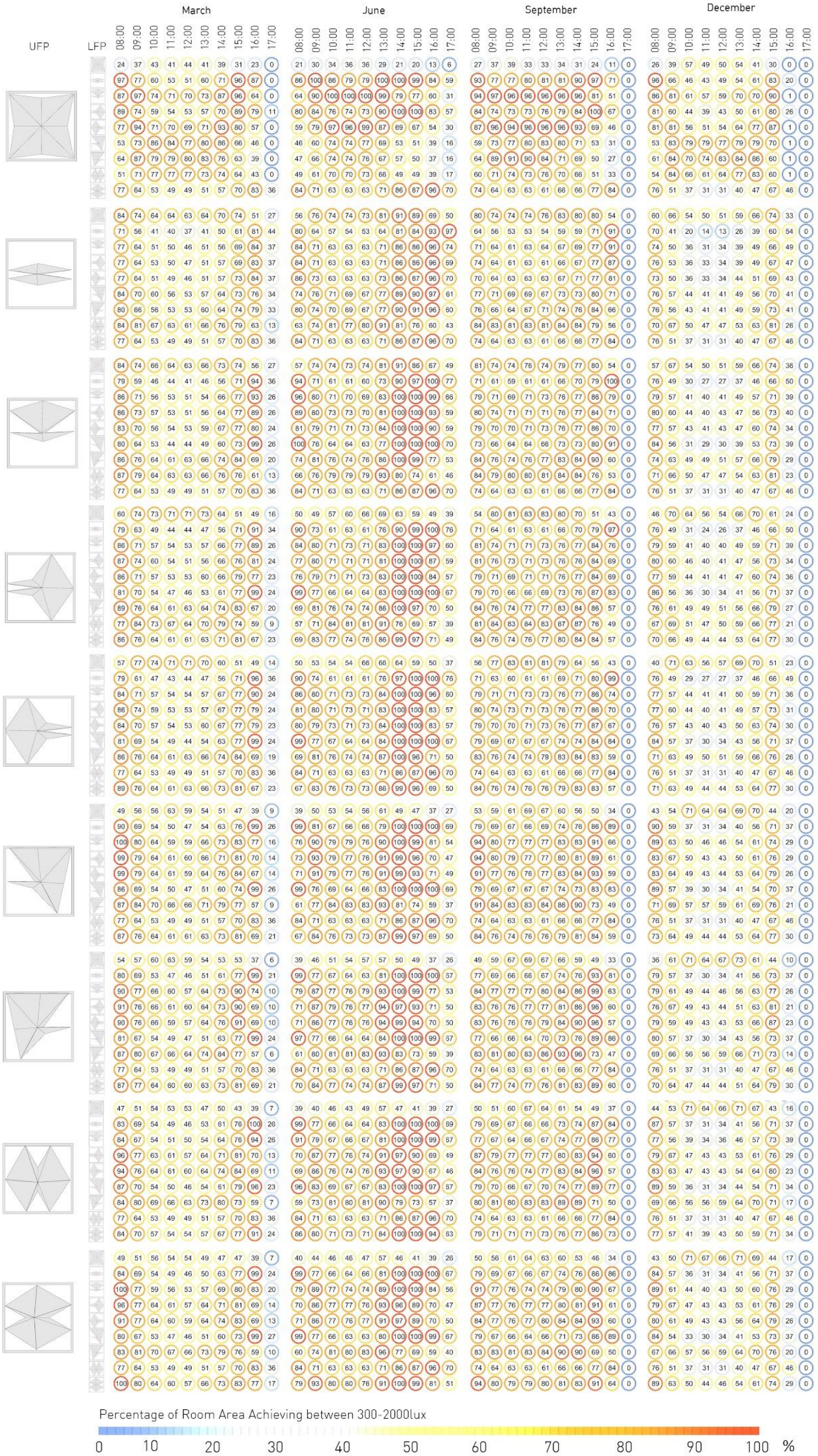

Figure 5: Useful Daylight Illuminance for 81 Cases

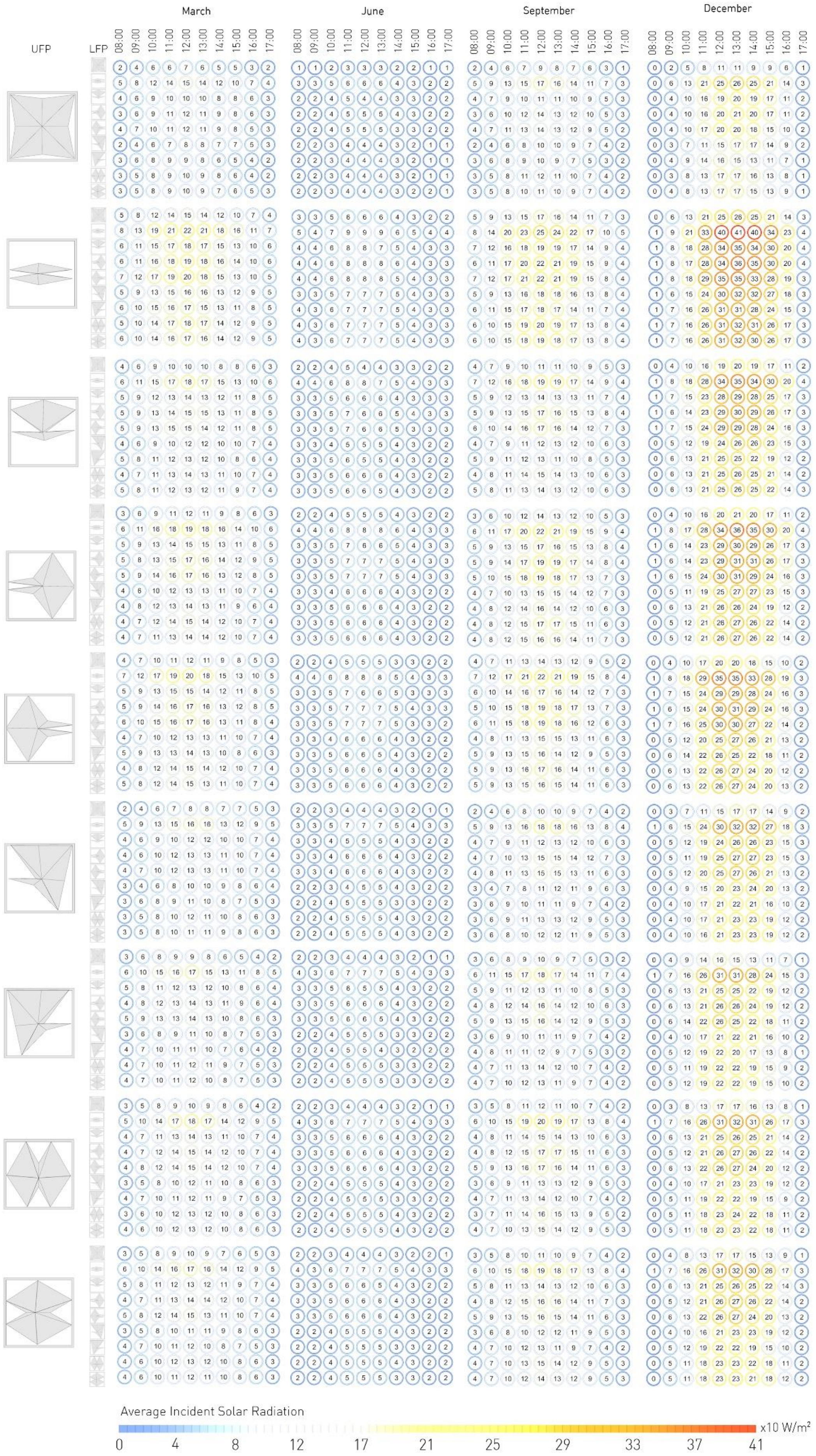

Figure 6: Average Incident Solar Radiation for 81 Cases

A visual representation of the set of possibility space in relation to the two major performative objectives is illustrated in Figure 7 below.

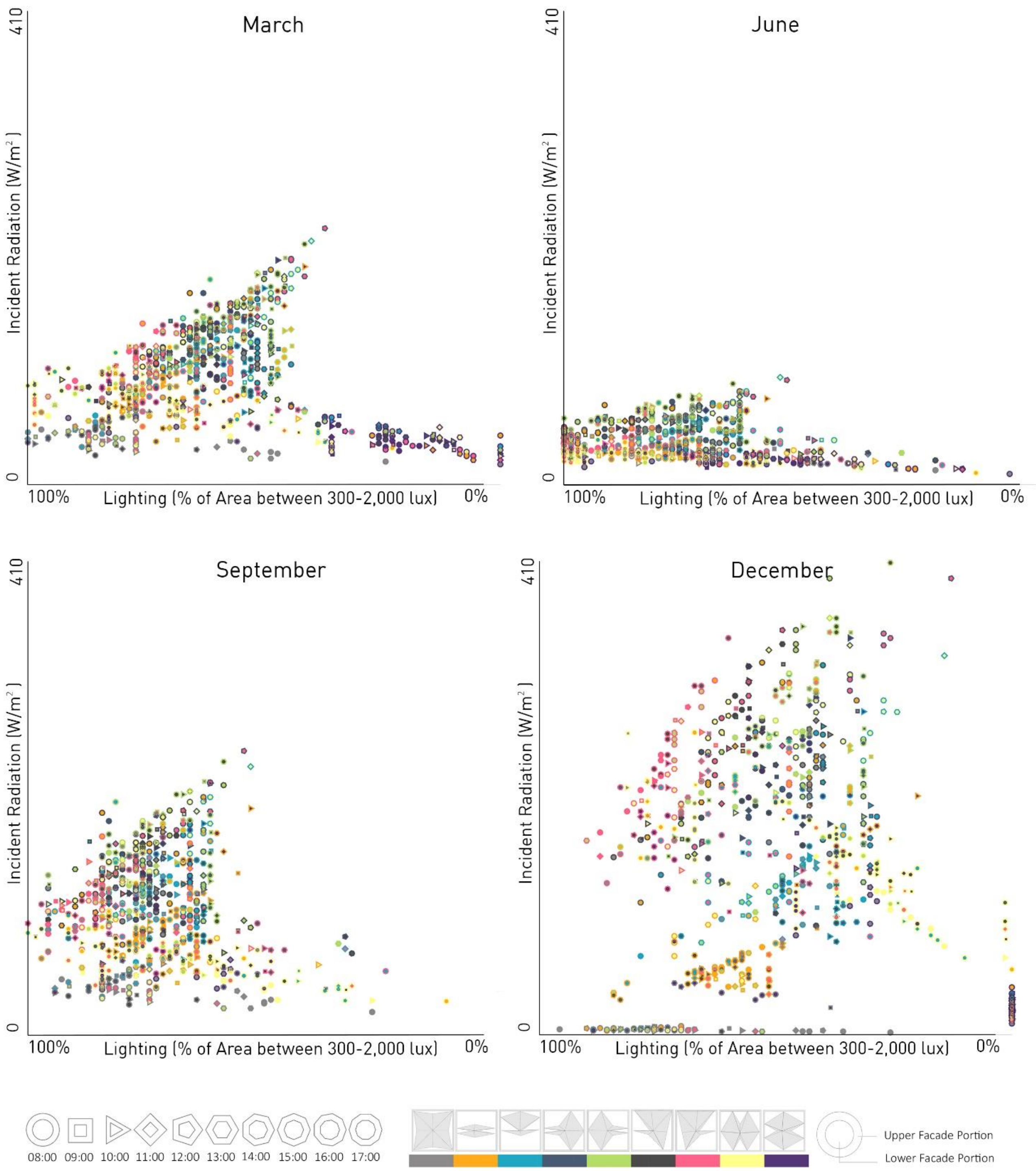

Figure 7: Solution Possibility Space

A larger spread of impact possibilities was witnessed in winter months, with the opposite happening in June, and distinct cases achieving the optimum performance for each. The two-layered (partitioned) façade versus one-layered (non-partitioned) façade cases showed an increase in the possibility space. A distinction between the two approaches in the solution space was created to better understand this design decision's impact on system performance, an illustration shown below in *Figure 8*. The increase in solution space due to the use of two-layered façade showed, not only a rise in diversity, but net improvements of both functions, solutions highlighted in *Figure 8* for two sample hours of the evaluated period.

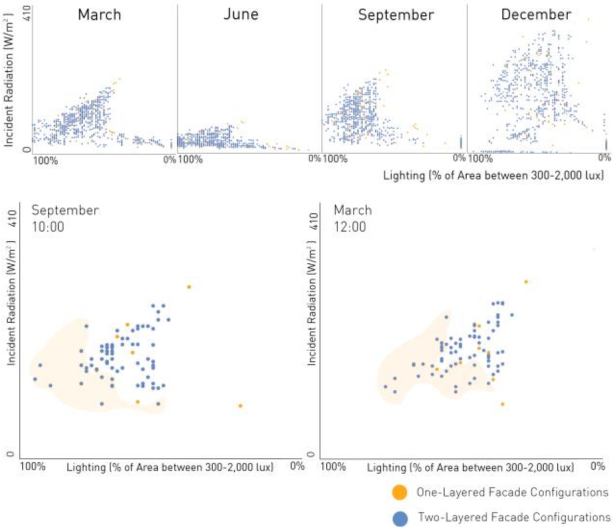

Figure 8: Partitioned versus Non-Partitioned Facades

The relation between the successful cases for illumination, identified as the one achieving a minimum of 75% of room area with illuminance levels between 300 and 2000 lux, geometry cases and time was highlighted through dividing the positive cases by ratio for each hour and each month. An illustration of the geometry's ratio of positive impact throughout time was developed as shown in *Figure 8*.

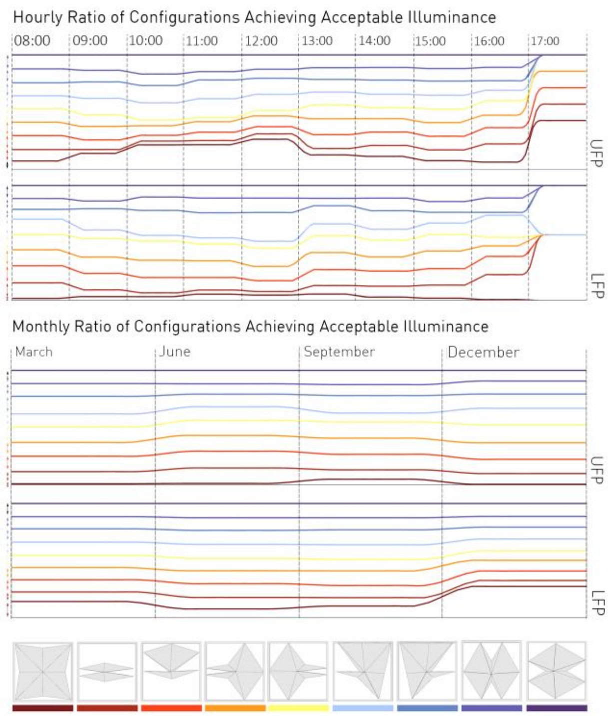

Figure 9: Illuminance Successful Cases - Hourly and Seasonal Ratios

An effectiveness of the closed configuration was observed during the mid-hours and later hours of the day in the upper façade portions, while a more dominating role in the lower façade portions during December and March, which are recognized by lower sun angles and lower radiative strength. A significant difference between the ratio of successful configurations for upper and lower portions show evidence of their different functions in achieving highest performance through complementary roles. Two optimum configurations were identified based on two difference hierarchies of performance objectives: illuminance-radiation-openness and radiation-illuminance-openness, shown respectively in Figure 11 and Figure 12.

The domination of the closed configuration on upper façade portions was clearly identified in the two cases. However, the daylighting objective case showed a higher diversity in the required combinations in contrast to a stricter change in the solar radiation case varying between three combinations for all hours. The focus on solar radiation for its case, showed at its optimal configuration significantly low daylighting performance, a higher compromise of the secondary performance objective.

To quantify the quality improvements by adding the façade portioning and the adaptability dimensions, a comparison was carried out for the most performing shading façades possible for static, adaptive, and layered facades, as shown below in *Figure 10*. This illustrative diagram compares the most performing shading façades possible for static, adaptive, and layered facades. The performance percentages are indicated besides each option from top to bottom as daylighting, radiation, and openness, respectively.

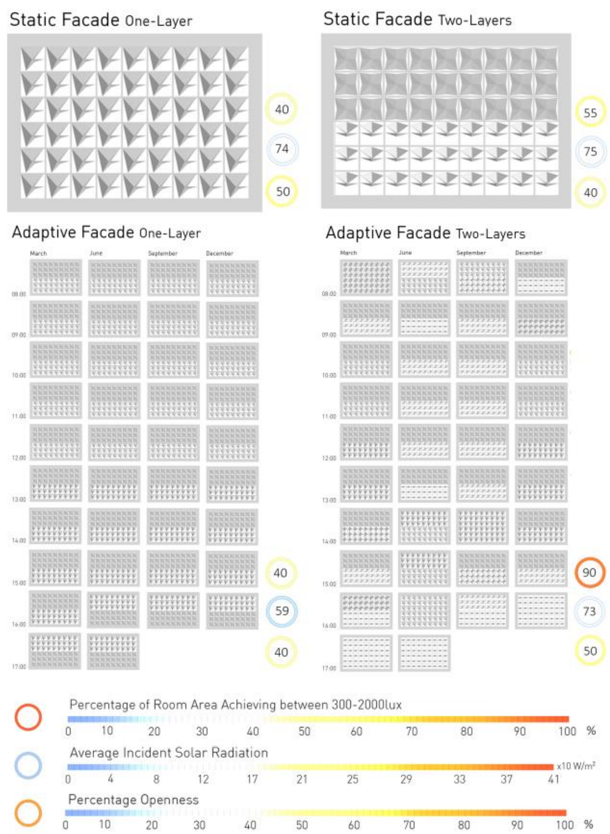

Figure 10: Comparative Cases - Portioning and Adaptability Dimensions

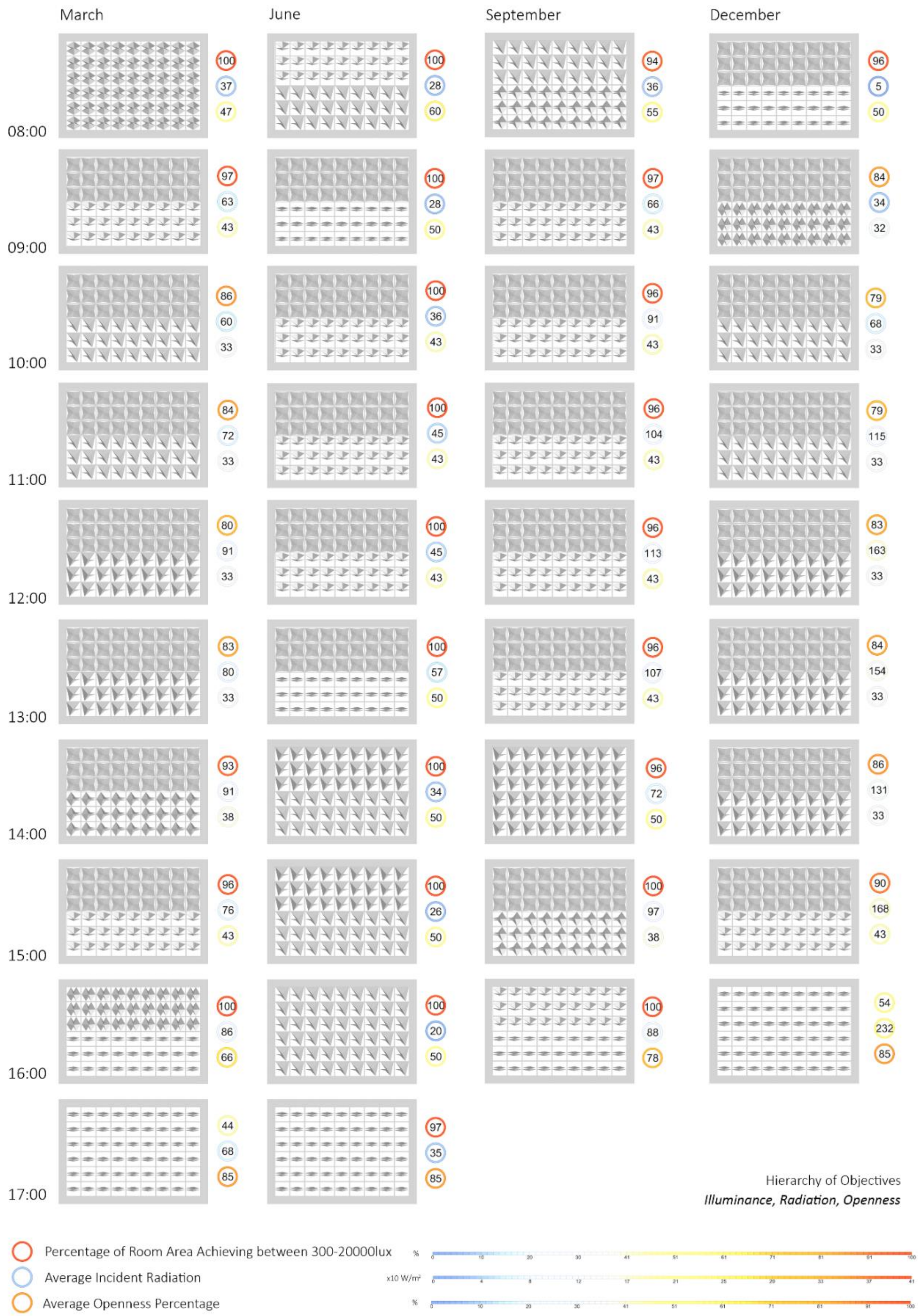

Figure 11: Adaptive Geometry Combinations for Optimum Illuminance Case

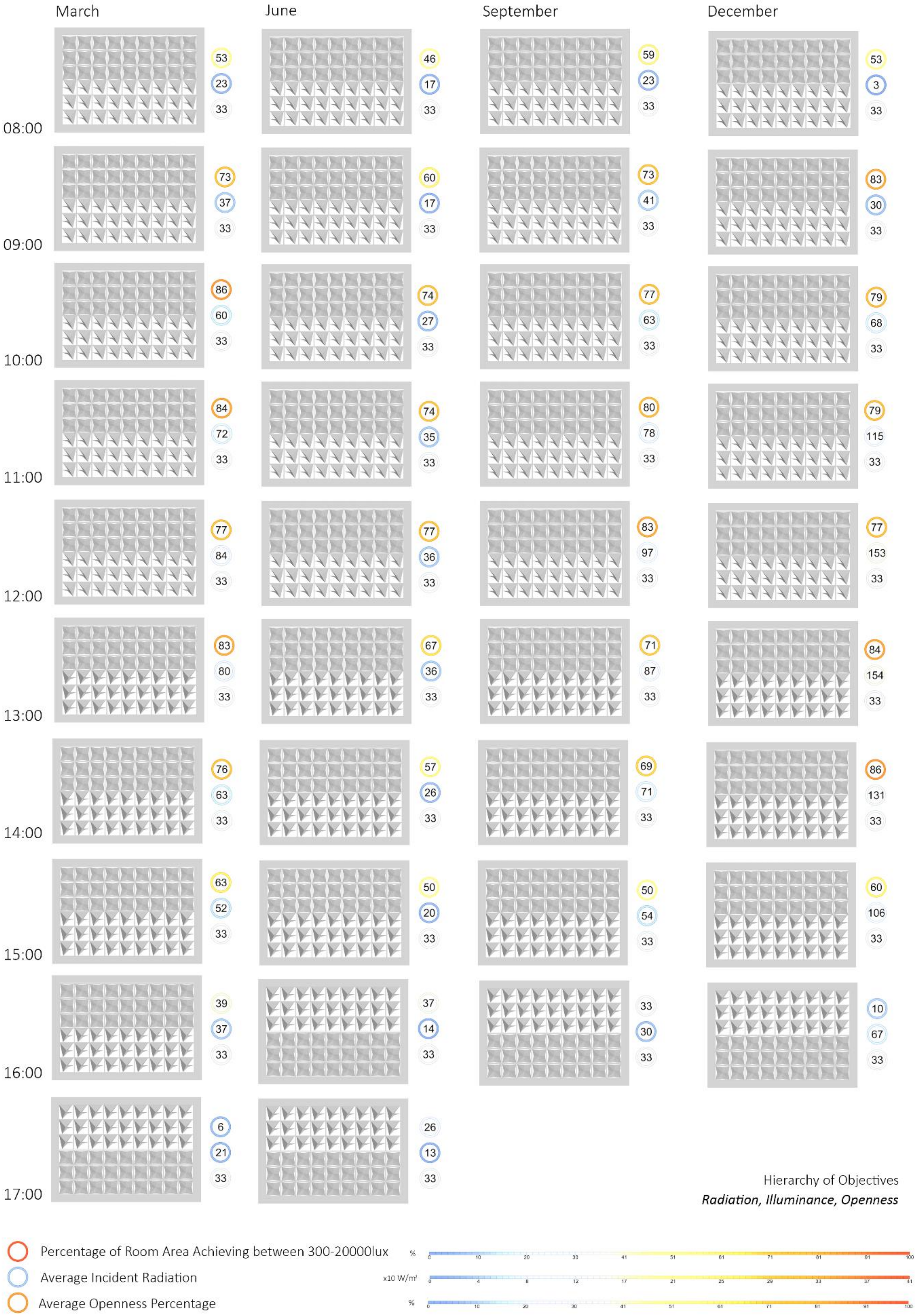

Figure 12: Adaptive Geometry Combinations for Optimum Radiation Case

The illuminance-optimal case showed an improvement of about 125% in daylighting from the base one-layer static façade case and 63% from the two-layer static façade case, while achieving the same incident radiation levels and openness. Additionally, the radiation-optimal case showed a 27% reduction in incident solar radiation from both the one-layer static and two-layer static cases while achieving the same level of daylight performance and openness. A stronger relation was found between façade portioning and daylighting than radiation and both achieved higher performances with adaptability.

Discussion

Providing differentiation through façade layering proved its suitability and higher performative capacities compared to systems that are limited to one component behaviour. The highest impact was on daylighting improvements, a recorded percentage increase of 38% from the best one layered façade; with an even larger improvement of 125% when adaptability dimension was added. The hierarchal sorting of objectives, applied for the identification of the most performing adaptive combinations, showed low daylighting values for the lowest radiations and a tendency for choosing the most closed configurations. This allowed for the evaluative weight to be concentrated on daylighting metrics, which inherently reduced excessive solar radiation using the 2000 lux threshold. The performative objectives increased daylighting performance, reduced incident solar radiation and increased openness, were set based on general and most influential weather requirements for Cairo, rather than to accommodate for the rarely needed seasonal and functional specificities. For instance, an average openness value for the façade was used, although it could have been more accurate to layer the performance calculations, with high values of openness only being sought for the range of human visual field. Designing for variations in hourly and seasonal impacts was preferred to including those changes in pre-defined objectives.

Limitations of this study include the restrictions that digital simulations inherently have in representing accurately contextual, environmental and material parameters, the unobstructed field and southern orientation that represent only a portion of the real context of the built environment and the 4-day year representative sample of Cairo's climatic needs and SMA behaviour. On the other hand, the brute force method for evaluating all alternatives in performance and all actuator-movement connections was preferred over optimization due to the computational feasibility of cases and for a more comprehensive understanding of parameters impact, in contrast to aggregated results.

Conclusion

The reliance on a binary on/off output and a system singularity for material-based adaptive facades was questioned in terms of their performative qualities. This study showed that the larger geometrical repertoire, adaptability, and façade layering allow the passive system to reach its higher performative potentials. Future work should aim to engineer the SMA-based façade systems to identify their limitations. Other performative and functional objectives, suitable for other climatic and architectural needs, can be targeted and designed for, increasing the scope of usability of such material-based activation systems.

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