Neighbourhood Shading Impacts on Passive Adaptive Façade Collective Behaviour

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Abstract. The past decade witnessed a shift in adaptive facades from energy-intensive complex systems to material-based actuated facades. The latter, however, were only developed with limited control in shape memory alloy applications, and more generally designed as independent components. The perception of the component within a system as a self-regulating entity was shown to widen the behavioural response and intelligence of an adaptive system in several projects. On the other hand, its range of impact and integration as a design factor were not targeted at full breadth in the literature. The study's objective was to investigate the incorporation of neighbourhood shading behaviour of a shape memory alloy-actuated façade component on the entire system. Based on a designed adaptive component, the research identifies the shading impact on the actuators' incident solar radiation as well as its hourly and seasonal range, and thus encourages a better prediction of collective behaviour.

Keywords: Solar Morphing Envelopes, Neighbourhood Shading, Collective Behaviour, Adaptive Facades.

1 Introduction

The past decade witnessed a shift in adaptive facades from energy-intensive complex systems to material-based actuated facades [7, 8, 14]. The latter, however, were generally developed for binary movements and limited control in shape memory alloy[1] (SMA) applications, and more generally designed as independent components.

The AIR Flower project, for instance, defined a composition of separate elements, and for which the resulting façade behaviour is similar to a system using a centralized actuation mechanism for all the components within the same orientation [16]. The latter

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[1] Shape memory alloys are smart materials which exhibit shape memory effect and super-elasticity properties when they undergo lattice phase transformations from a strong high temperature phase (austenite) to a softer low temperature phase (martensitic). [1, 3, 4, 10, 11]

is an approach that was implemented in Harvest Shade Screens where one SMA spring activated the rotations of all louvers within one panel for cost effectiveness and resource efficiency [6].
The perception of the component within a system as a self-regulating entity was shown to widen the behavioural response and intelligence of the system, an approach implemented by the three other projects. Piraeous Tower facade's sine-wave geometry was produced by the vertically located SMAs to elliptical openings of a continuous stretched material and showed a dependence between individual component responses and the aggregate impact. Shading neighbours delay component actuations, in addition to the gradient effect they achieve due to the material flexibility thresholds [2]. Similarly, the Self-Adaptive Membrane and Adaptive Skins projects' system nature gave rise to movement patterns [5, 15]. Self-shading, although not purposely accommodated for in the design, constituted an essential aspect of the overall behaviour and a collective impact of individual differences. On the other hand, its range of impact and integration as a design factor were not targeted at full breadth in the literature.

The objective of this study was to investigate the incorporation of neighbourhood and self-shading behaviour of a shape memory alloy actuated façade on the adaptive system in its entirety as well as the components design in terms of behaviour and performance. This explores impacts on the generation of actuation patterns that are not based on uniformity. Based on a designed adaptive component, the research identifies the extent of the self-shading impact on the actuators' incident solar radiation as well as its hourly and seasonal range and explores the pattern variance instilled by the collective generative behaviour.

2 Methodology

To investigate the impacts of neighbourhood shading on a material-based adaptive façade collective behaviour, the evaluation of neighbourhood shading cases was carried out and compared. The strategy and implementation process of this research are detailed in the following sub-sections including the climatic context, the case study shading geometry, the simulation environment, the computational strategy, and the evaluation method.

2.1 Climatic Context and Case Study Shading Geometry

A south-oriented façade was evaluated for the purposes of the study to provide an assessment environment that accommodates for the largest shading variations. The location of the façade was identified as Cairo, capital of Egypt, for which the case study shading geometry was designed and which is characterized by being a hot arid climate with a clear sky for the majority of the year [12]. The case study adaptive component [9] consists of an origami-based geometry of 400mm by 400mm that is actuated by four shape memory alloys located at four corners. These can produce nine distinct forms, illustrated in Fig. 1, through linear movements up, side and/or down. These were designed to be placed side by side to generate a grid of shading.

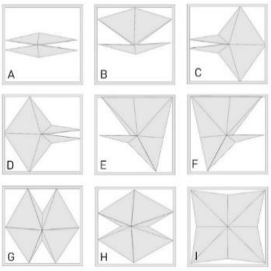

Fig. 1. Nine Forms Generated by Origami-Adaptive Component [9]

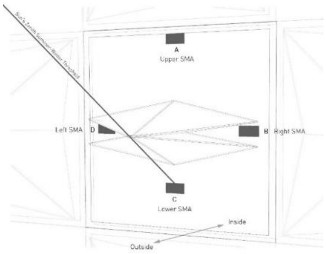

Fig. 2. 4-SMAs Location within Shading Component [9]

2.2 Simulation Environment

A digital model was developed in Rhino3D modelling software along with its parametric plugin Grasshopper for simulating origami movements with forces tailored to the four shape memory alloy limitations and automating the simulation process. An analysis grid of 100mm by 100mm, located 100mm behind the shading geometry, was used to represent the building surface for the incident solar radiation simulation. Each SMA irradiation was identified by the average of four analysis points based on their specific locations within the component, illustrated in Fig. 2. For each of the studied cases, a solar irradiation analysis was performed through Ladybug[2], using Radiance engine, for a selection of 40 hours acting as the representative sample of the year. The latter was defined as hours from 08:00 to 17:00 on the equinoxes and solstices. Two distinct set of data were collected from the simulation: the solar irradiation on the building surface and the four SMAs incident solar radiation values; used for the corresponding evaluation of the neighbourhood shading performative and behavioural impacts, distinctly shown in Fig. 3.

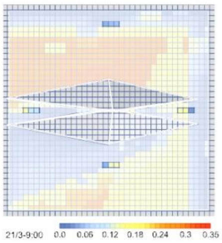

Fig. 3. Solar Irradiation Analysis (Building Surface and 4-SMAs) [9]

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[2] Ladybug is an open source plugin utilised for environmental performative assessments and visualisation using data extracted from EnergyPlus weather files [13].

2.3 Computational Strategy

To grab an understanding of the shading impact of all geometries during all times, incident solar radiations had to be computed for all possible combinations. Since each panel have the possibility of nine geometrical options, a sample grid of 9x6 for instance, would mean 9^{54} possibilities for the adaptive shading skin and a much higher number for any larger grid. The computational irrationality of carrying out that number led to the definition of shading to be considered as a product of only its four direct neighbours, resulting in a case reduction to about 60,000 possibilities.

These possibilities represent all possible configurations of any grid size. The Von Neumann neighbourhood approach, as shown in Fig. 4, can be justified by the low probability of shading's farther reach.

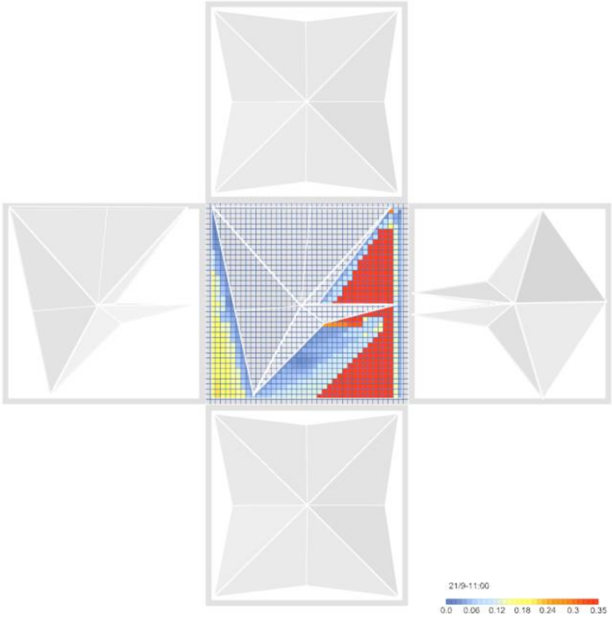

Fig. 4. Component Neighbourhood for Shading Impacts

The incident solar radiation values for these configurations were computed, stored for analysis, and used in analysing shading patterns.

2.4 Evaluation Method

The shading impact was evaluated using an impact factor defined as the percentage change between the incident solar radiation of the base case (non-deployed geometry with no neighbours) and each neighbouring case. A comparative assessment of the impact factor of the 4 neighbouring geometries on each one of the 4 SMAs for each of the 40 hours under study was carried out.

3 Results and Analysis

The integrated system's neighbourhood and self-shading impact factor was calculated for each set of neighbours and each SMA as an average of the 40 hours and illustrated in Fig. 5 below. All the results were represented in a table hierarchy where the upper sided hierarchies are defined respectively as upper neighbours with a sub-hierarchy of right neighbours, and lower neighbours with a sub-hierarchy of left neighbours.

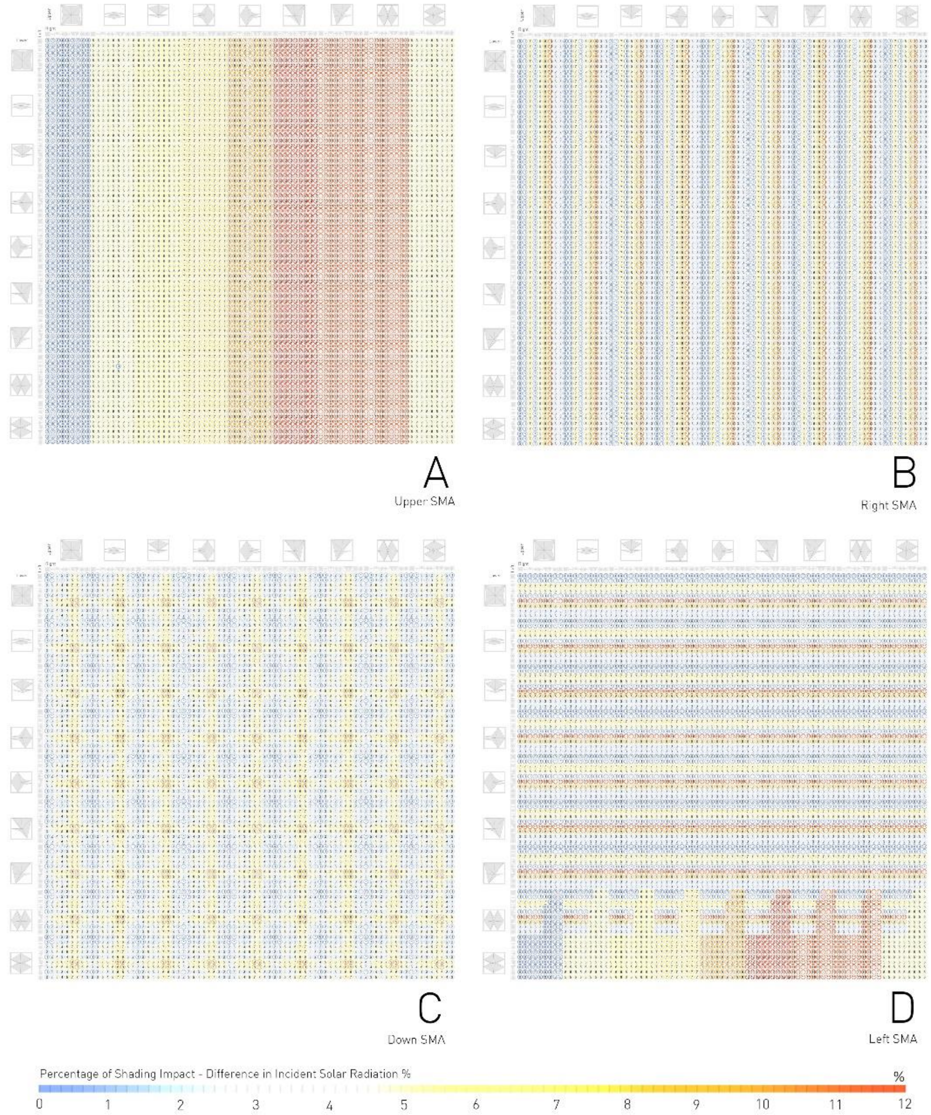

Fig. 5. Average Shading Impacts of all Neighbours per SMA

An observed pattern of impacts was distinct for each SMA, where the upper, right, and left SMAs were only impacted by their corresponding neighbour, the lower SMA by the right and left neighbours, with zero impact from the lower neighbour. The impacted cases were further explored on an hourly basis, identified below in Fig. 6 in which zero impact conditions were eliminated.

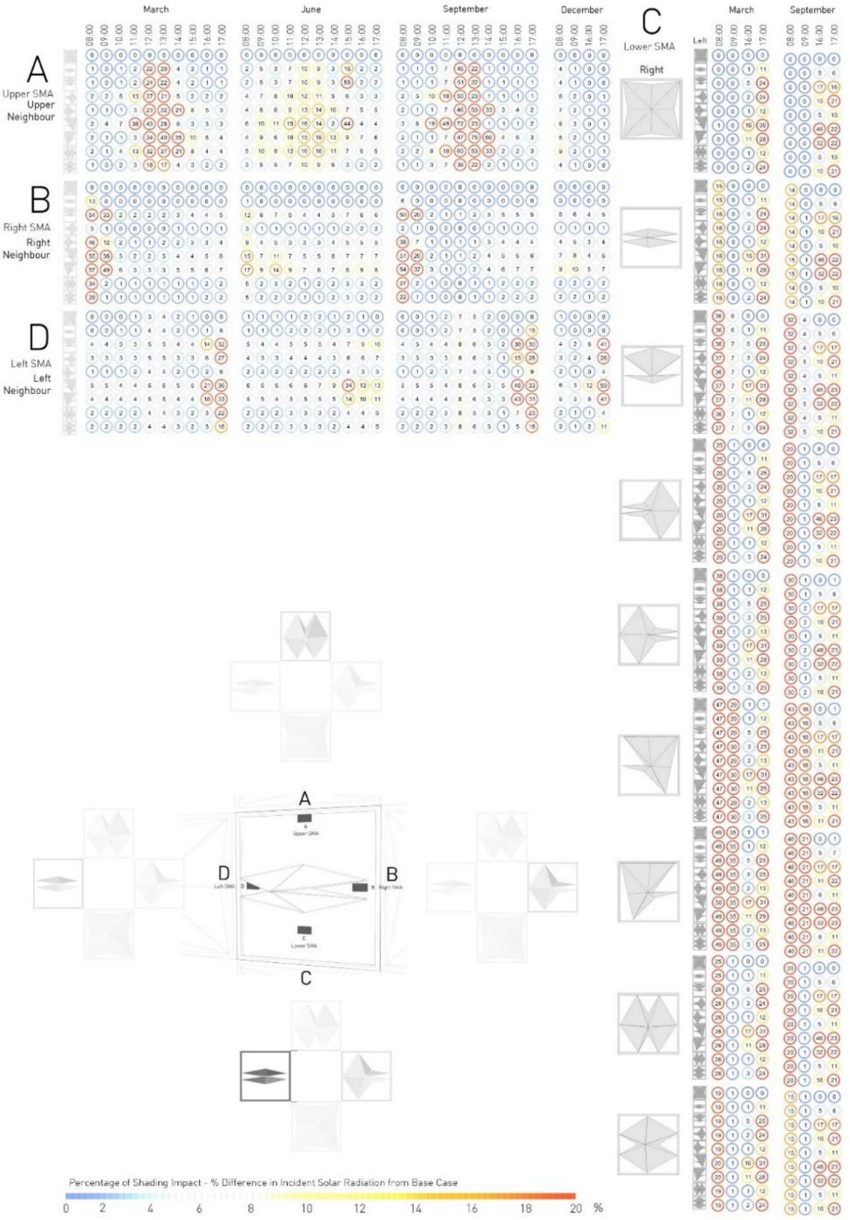

Fig. 6. Hourly Shading Impact Percentage of All Cases of Significance

The relation between the shading impacted cases, identified as the cases achieving a percentage change greater than 10%, geometry configurations 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 impact throughout time was developed as shown in Fig. 7 and Fig. 8.

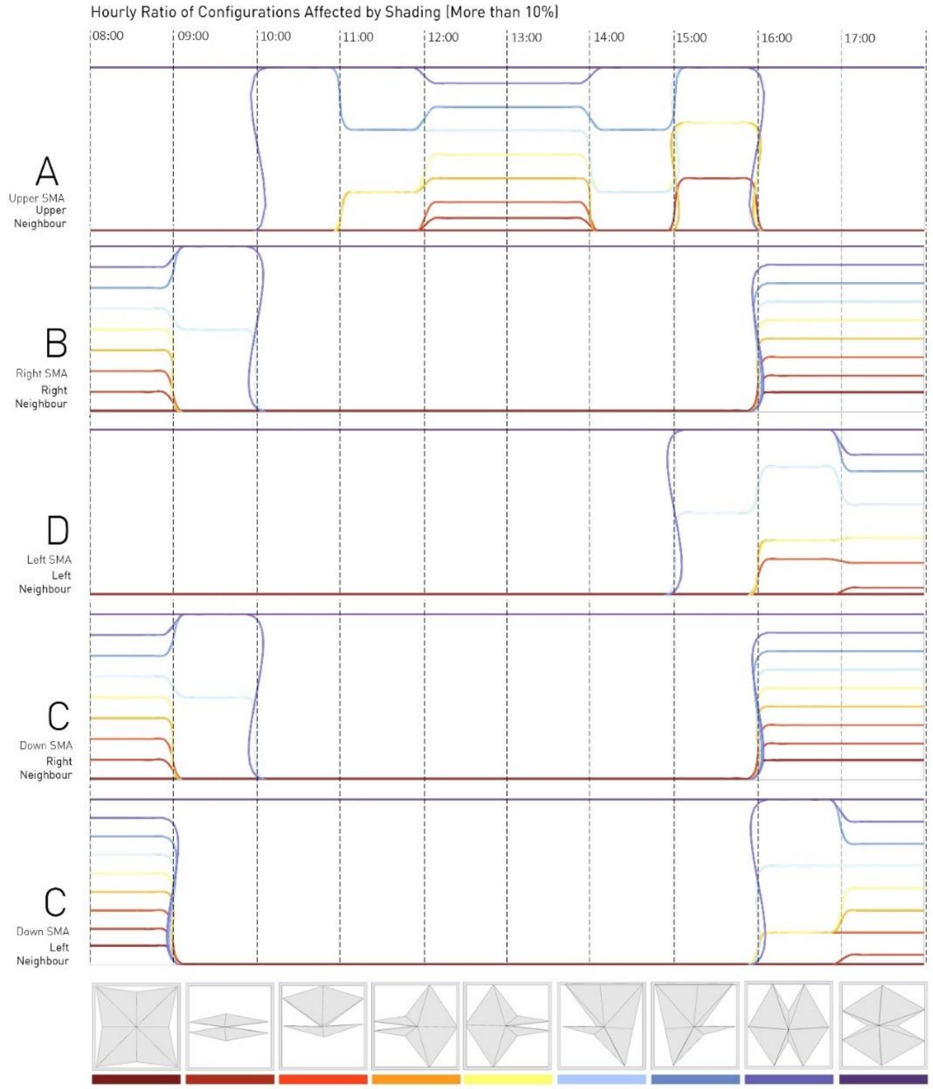

Fig. 7. Shading Impacted Cases - Hourly Ratios

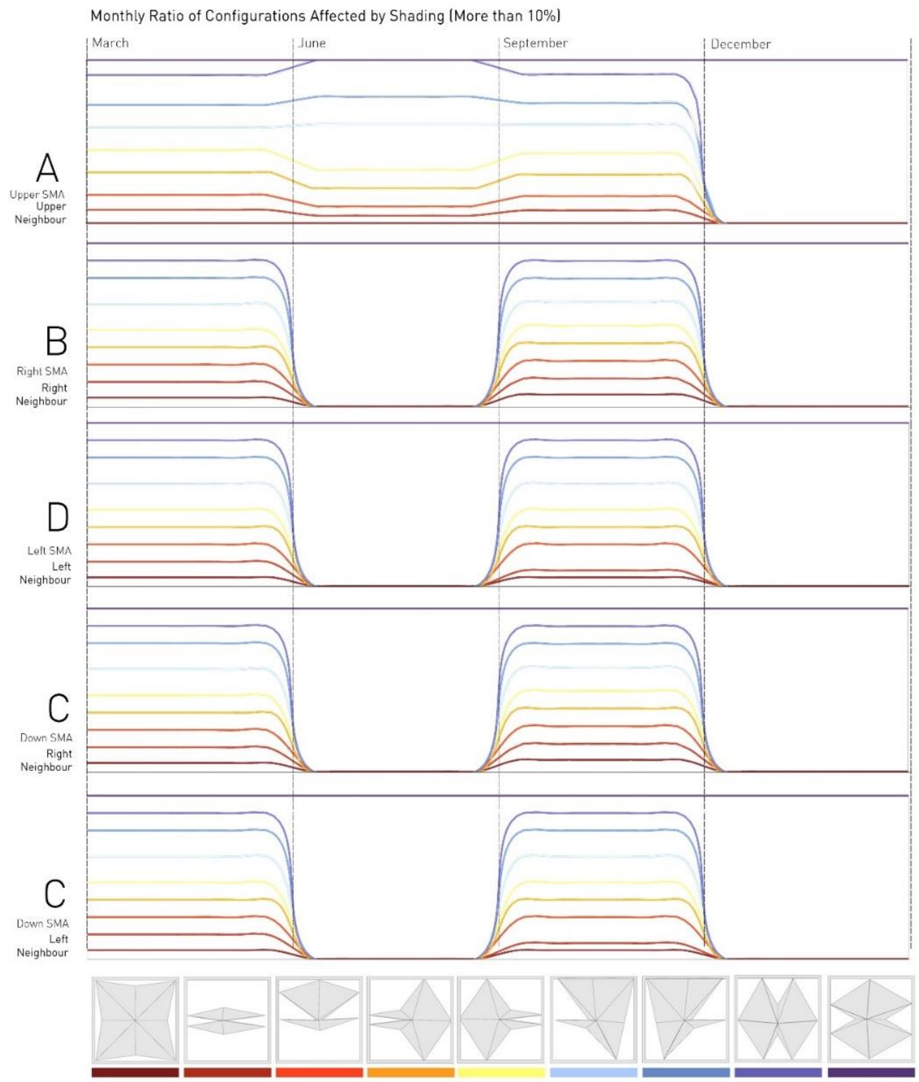

Fig. 8. Shading Impacted Cases - Hourly Ratios

These diagrammatic illustrations of cases with high shading impacts identified the significantly different shading impacts and allow for a distinct time-based and geometry-based separation of cases. For hours ranging from 10:00 to 15:00, the only influential actuator, for instance, was the upper one, affected only by its upper neighbour; while all other neighbours and SMAs were completely unaffected during this period, in contrast to being highly affected during early and late hours of the day.

During December, no shading impacts were found, which can be explained by the lower sun positions. The geometrical configuration showed as well diverse shading influences, however not as highly distinct as the time-based differentials. The right and left neighbours’ geometrical configurations showed mirror impacts for early and late hours of the day.

The shading’s effect extent was as well observed through its performative impact: the incident radiation on the building surface, shown in Fig. 9. It should be noted that due to the 10cm gap between the shading component and the building surface, the illustrated impact on the building façade constitute a greatly attenuated expression of the actual effects on the four SMA solar incidence.

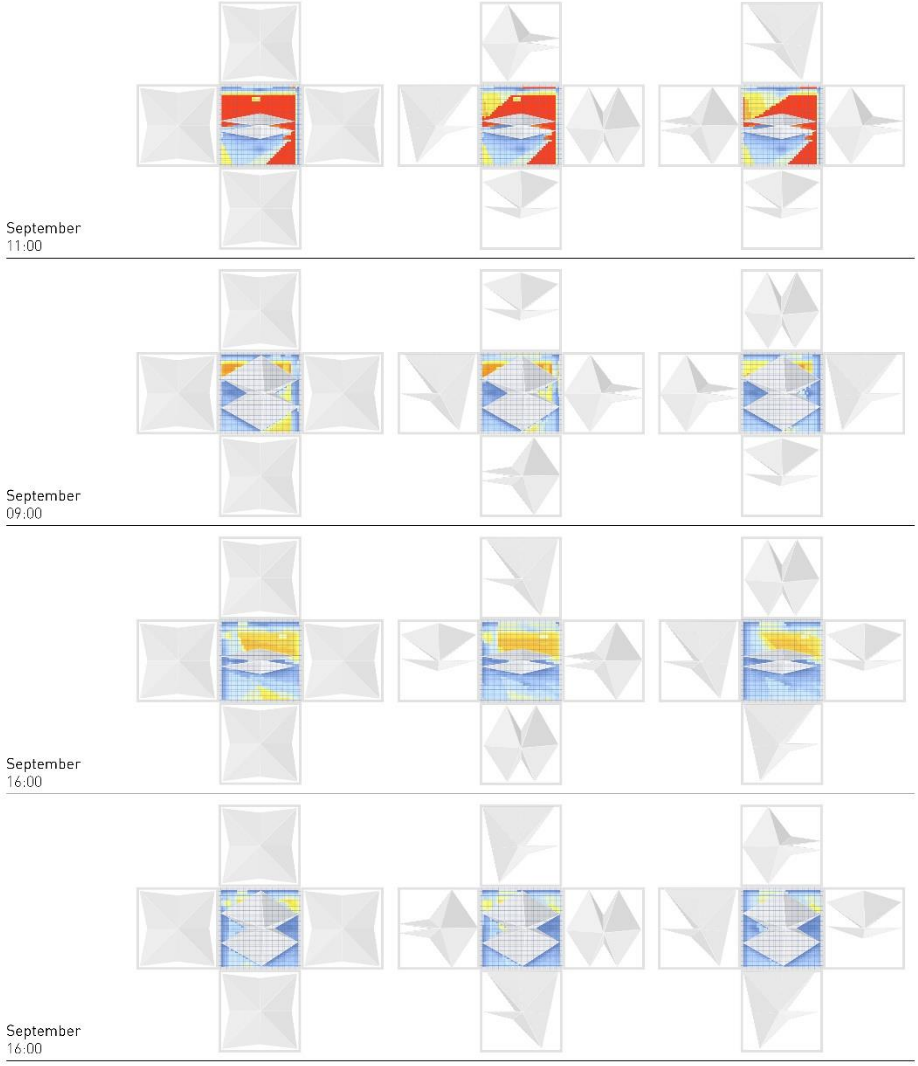

Fig. 9. Neighbour Shading Impact on Incident Radiation on Building Surface

For the same recorded hours, different shading patterns were observed with varying neighbouring geometries, where specific geometries achieved greatest differentials in the mornings, others in the afternoon, with a more general combinatory effect for the upper SMA during mid-day. Although the impacts were restricted to a limited range of hours, it reached up to 75%, a radiation difference of $300\ Wh \cdot m^{-2}$. The latter results in a pattern differential of great relevance to performance and behaviour of the SMA-adaptive solar shading and of subtle but interesting generative nature.

4 Discussion

The system's neighbourhood and self-shading impacts showed differentials and the potential for some degree of generative behaviours in the designed system. The Von Neumann neighbourhood definition used for improving computational time efficiency for irradiation calculations allowed for a decrease in the number of simulated configurations to 60,000 cases. The lower shading impacts of other façade portions constituted the basis for this compromise in identifying comprehensive shading patterns. Within the evaluated cases, the lower neighbour showed no impacts thus allowing for further reductions in computational time and a quicker design-testing loop to about 6,500 cases (10% of the original configurations).

Recorded incident solar radiation on the four SMA and the building surface allowed for the identification of the most impactful geometries as well as the time and seasonal factors impact. Shading impact factors ranged from 0% to 75%, 0 to $300\ Wh \cdot m^{-2}$. The lower SMA was the actuator with the highest percentage change due to being the only actuator influenced, not by one, but two different neighbours (the right and left neighbours). The largest shading impacts were found during the late mornings and late afternoons, for the right and left portions, while mid-day hours were highly impacted upper portions. December showed no impacts, June minor impacts in contrast to March and September months which had the highest with a steady distribution among geometrical forms.

The flattest geometry, the opaquest configuration, showed a no effect on its neighbouring shading components. The periods from 09:00 to 11:00 and 14:00 to 16:00 were the hours in which each geometrical configuration showed a different proportional contribution to shading. The performative influence of shading was observed to be significant and highly affected by the geometrical neighbourhood configurations, which reflects the necessary consideration of designed geometries and behaviours for higher performing facades. Significantly identified at specific time periods, the self-shading dimension can show interesting and subtle changes in a façade's behaviour.

The integration of that characteristic into the design of the system component could allow for higher performance and better system predictions. An understanding of the time-based and geometry-based influences analysed in this research provide an opportunity for designers to carefully consider only relevant cases of shading thus reducing significantly computational time and promoting a more efficient and informed design-behaviour-performance testing cycle.

The scope and limitations of this study constitute a necessary dimension for the proper interpretation of results. Firstly, the solar irradiation was simulated based on a digital simulation using Cairo's weather data file for a south-oriented façade with no obstructions using recommended simulation resolution. A calibration using real life measurements could be a further step towards additional validation of results. Secondly, the 40-hour representative sample reflected the year's peak changes rather than the continuous climatic behaviour. Thirdly, the solar irradiation here is studied in isolation of other climatic factors such as wind, humidity and sky coverage which can have an impact on the adaptive component's behaviour. On the other hand, the brute force method of testing all cases, with the limitation of Von Neumann neighbourhood, provided the means to effectively evaluate both the individual impacts of geometries, neighbours, SMA locations and time on the shading factor, as well as their aggregated effect.

5 Conclusion

Among the greatest challenges of designing material-based actuated responses is their sole reliance on the material's behavioural response to certain climatic and situational factors which can be hardly controlled. Slight contextual differences lead to significant behavioural changes and thus should be accommodated for, to achieve desired formal and performative outputs. This shall not be presented as a constraint as much as it should be as an opportunity of exploring the material capacities to self-regulate a system, based on an understanding of its logics and structure, for either performative or non-performatives goals. A global design of an adaptive façade is thus preferred over an isolated component design due to the latter's inability to accurately represent responses highly affected by the self-shading dimension, one that was capable of creating an impact factor of up to 75%.

By comprehending the neighbourhood shading impacts, the computational intelligence of natural collective systems can be promoted through careful informed design decisions for an adaptive system, studied here in the case of shape memory alloys (SMAs). These decisions include the geometrical form, scale, proportions, and orientations of the shading, as well as the location of the actuators relative to the component and its neighbours. Despite the context- and geometry-specific nature of the study, shading impact behavioural and performative outcomes can be transferable on general terms to similar hot arid climates for the time-based impacts as well as partially considered for similar geometrical forms. However, they cannot be utilized for facades oriented differently due to the strict difference in solar angles and exposure.

Future design studies in the field of material-based actuated adaptive facades should thus aim to integrate neighbourhood shading on component design decisions as well as efficiently focus its effect on the relevant time periods and sun-geometry shading angles. Performative thermal façade implications should be utilized for informing design decisions rather than acting as a passive factor; and other façade functional and environmental objectives can be additionally studied to identify their relationship with neighbourhood shading behaviour. The aspiration is for a highly performative zero-energy adaptive architecture that is self-regulating by an instilled computational collective intelligence.

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