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Shape grammar and kinetic façade shading systems: A novel approach to climate adaptive building design with a real time performance evaluation

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Abstract: The concept of a dynamic building enclosure is relatively radical and unexplored area in sustainable architectural design and engineering and as such could be considered a new paradigm. In this research, a novel application of shape grammar approach to design of kinetic façade shading systems has been discussed, inspired by vernacular Vietnamese architectural patterns and parametric generative design. The research reports on the system development and testing, exploring different façade shading configurations and evaluating their performance based on the real-time monitoring of daylight and heat gains, using wireless sensor technology. The strategy for BIM integrated sustainable design analysis (SDA) has also been deliberated, as a framework for exploring the integration of proposed building management system (BMS) into smart building environments (SBEs).

Keywords: kinetic shading, shape grammar, parametric patterns, performance monitoring, smart building environments.

1. Introduction

In recent times building performance research has identified that forces acting on buildings (e.g. climate, energies, information, human) are not static and fixed, but transitory and fluctuating instead. This has significance for the building envelope design which must transcend its role as mere protective envelope separating inside from outside. Building façades are increasingly understood as complex systems of material assemblies that are adaptable to climate and energy demands. More recently, they are equipped with higher performance materials, sensors, actuators and computerised intelligence that support automated dynamic operations and functionalities, such as regulating a building's light, air and sound transmission, thermal comfort, and interior air quality (Velikov and Thun, 2013).

Adaptive facades can provide opportunities for significant reductions in building energy use and CO_2 emissions, whilst at the same time having a positive impact on the quality of the indoor environment. A number of different types of adaptive façade concepts (materials, components and systems) have already been developed, and an increase in emerging, innovative solutions is expected in the near future. Adaptive facades are identified as promising technological solutions for contributing towards sustainability targets of the 21st century (Loonen et al, 2015).

This research is inspired by traditional patterns and ornaments seen a symbol of intercultural communication, especially in the era of globalisation when many cultures are subjected to substantial transformations and beginning to lose their original traditions. Vietnam is one of those. Using Shape Grammar approach, the proposed research aspires to create prototypes of innovative façade systems that satisfy building performance demands such as energy consumption and indoor comfort, whilst protecting cultural identity which had been somewhat lost in modern era.

2. Shape Grammar Development

2.1. Vietnamese Spatial Patterns and Designs

Patterns are a fundamental feature of spatial design (interior, architectural, urban and landscape). The term ‘pattern’ is from the Latin ‘pater’, or ‘patronus’, meaning father, patron, protector or master, from which is derived the notion of pattern as a model, example or mould. The modern concept of pattern is as repeating units, arrangements or developments of identical or similar elements. This diversity of meanings aims to the multiple roles of pattern in the creation, reproduction and evolution of spatial arrangements.

The patterns emerging from the interactions between these multiple systems are produced at a number of different dimensional, temporal and scalar levels, including the spectrum of natural and man-made patterns. As process (method, technique) and as product (object, material, form), patterns, like typologies and programmes, are also repeated in human-imposed spatial design solutions, concepts and effects (Garcia 2009,). Recently, new techniques and spatial layout theories are emerging, such as generative, algorithmic and parametric design approaches, allowing new types of spatial pattern, sometimes never seen before, to occur. This research merges both traditional and modern within the environmental performance context, considering the potentials of novel generative patterns design approaches in relation to the design of modern building façade systems and components.

In terms of socio-cultural impact, a compact symbolic form patterns can provide not only information about the cultural history of an ethnic group but also act as catalyst of self-identification in the society, contributing to cultural and spiritual self-development. They represent a form of universal understanding in a visual symbolic form, a visual archetype of decorative forms that signify cultural identity.

In East Asia, such as China and Vietnam, principles of Euclidean and geometric transformations can be often be found on the Asian lattices which are works of an important artistic and cultural value (Majewski et al. 2015), see Fig. 1. These patterns and their visual composition are an essential part of “shape grammar” development in this research.

Fig.1 Left: Decorative lattice screens as means of passive ventilation and light control. Right: rotatable door panels with vertical louvres.

2.3. Parametric/Generative Design in Architecture

The term generative design, or algorithmic design, has been used to define computer-generated geometric processes that are predominantly numerically controlled and parametrically constrained. Rooted in the mathematics of patterns, generative design lets designers to create a sequence of relationships that are applied to a module, or modules, in order to generate shapes and forms, or to intelligently control modelling by programming a series of instructions (Singh et al 2012).

In generative design, digital computation allows designers to write and use algorithms to generate geometric form, in effect, creating a rule-based environment for designs. An advantage of such processes is that they are inherently parametric. Changes can be applied to this system automatically, so the designer no longer has to manually update aspects of the design.

To assist designers to write scripts in order to create parametric models, Visual Programming (VP) was introduced. Myers (1990) identified visual programing “a system that allows user to specify a program in a two-(or more)-dimensional fashion”. Halbert (1990) described benefit of visual programing for design practitioners as a crucial tool for non-programmers to be able to make complex programs with little formal training. Undoubtedly, visual programing straddles two disciplines, design and programming, both of which have evolved immensely, making parametric modelling increasingly accessible to the design practice via software such as Grasshopper and Dynamo (Eleftheria and Theodoros 2017), see Fig.2.

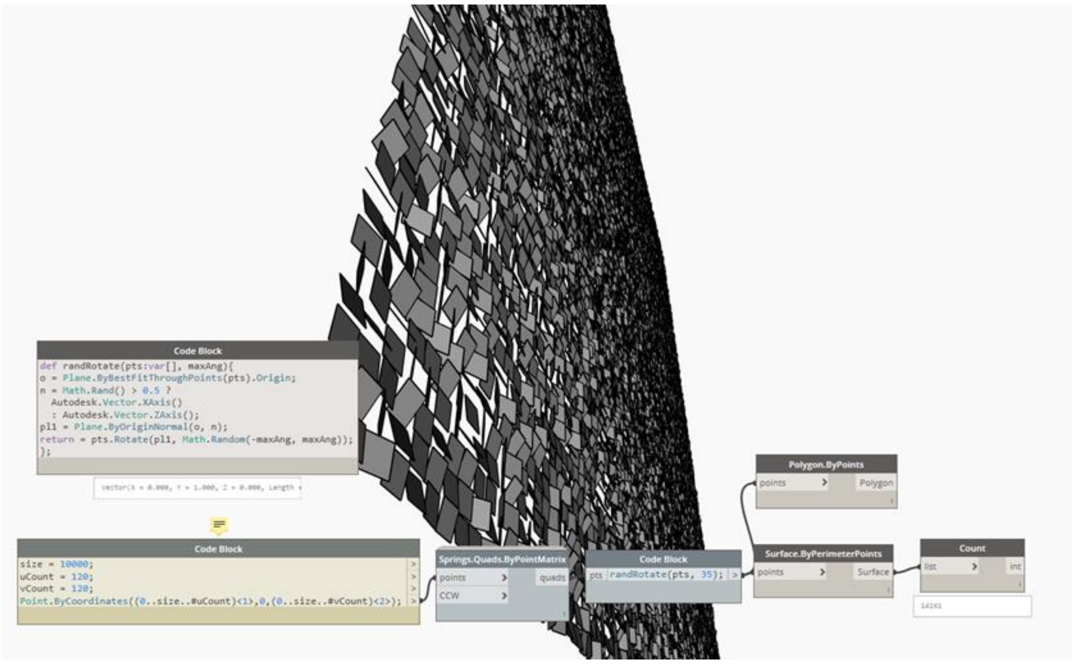

Fig 2. Visual programming Dynamo script for a kinetic façade design (Source: Author)

2.2. Shape Grammars Development

Shape grammars (SGs) have been used effectively to explore design spaces in numerous design contexts (Strobbe 2015), to both analyse existing motifs and generate new parametric designs. Current implementations have demonstrated how designers take advantages of SGs generative capability [6]. Indeed, shape grammar has been used to capture the cultural gene of designs of for example Chinese ice-ray lattice designs (Stiny 1977) , the design of Mughul gardens (Stiny 1980), Queen Anne style houses (Fleming 1987), Taiwanese traditional vernacular residences (Chiou et al 1995), traditional Turkish houses (Cagdas 1996), classical Ottoman mosques (Sener et al 2008) and Siza's Malagueira houses (Duarte 2001). Most of these studies concentrate on spatial layout planning or in other words, two-dimensional shapes transformations on a horizontal plane, based on basic input parameters of space such as length, width, etc.

In this research, a shape grammar for typical Vietnamese lattice designs was developed, found on doors and windows used as decorative screens as well as means of passive ventilation and light control. They typically are on vertical planes and, in this research, serve a different purpose – designing and controlling the shading opening (façade aperture) to adapt to external climate conditions. Their potential was evaluated in terms of indoor comfort, namely effectiveness of natural daylight control and protection against excessive heat gains. To demonstrate this, Shape Grammar Interpreter (©SourceForge) is used for shape-generating process because of its ability to effectively configure rules and visually display results by producing a multitude of complex composites (see Fig 2).

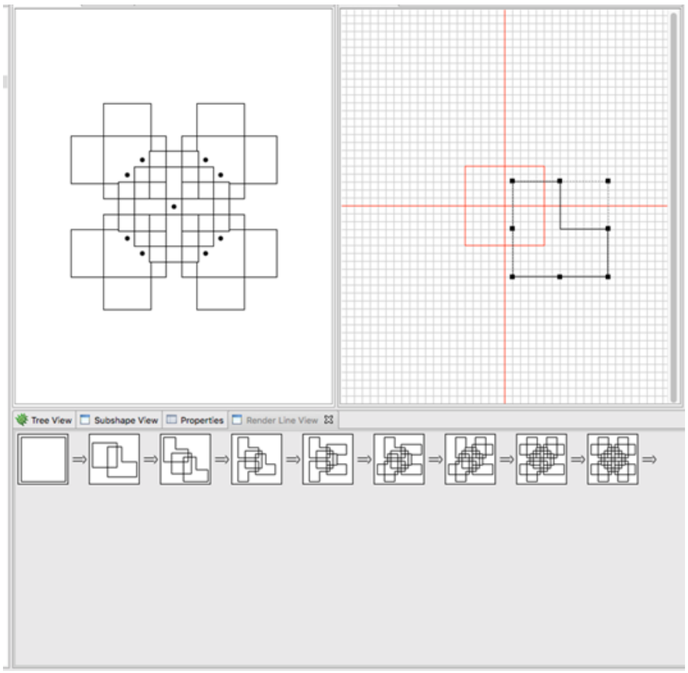

Fig 3. An example of Shape grammar interpreter uses straight lines as basic elements

The method proposed in this research is to apply shapes extracted from the lattice patterns found in literature (like I, L, S, H shapes or combination of them) in given SG computation process, which use two inputs: an initial shape and a shape transformation rule(s), where the rule and its repetition functions as a complex shape generator (see Fig. 3). In fact, each node of the lattice represents a shape element that is a maximal shape of a combination of such elements including both sub-shapes that are parts of the initial shape description and emergent shapes.

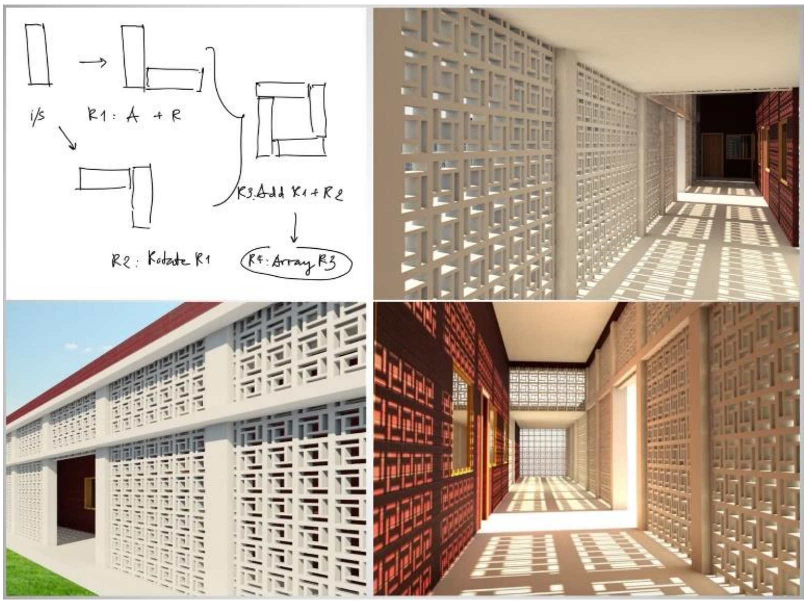

Fig 4. A concept of solar shading, for a corridor, made of similar shape and rules shown in Fig 3.

The development begins with defining a vocabulary of two dimensional shapes and their transformation rules. The shapes in a vocabulary of these scenarios are made up of the various elements that form the lattices, for example, frame, sub-frame and blocks. Indeed, an initial shape "I" (for rectangle shapes) and 2-d transforming rules, such as move, rotate, add, join and mirror are used. Figures 4 demonstrates how simple rules can quickly generate complex composites, which could be legibly used in the architectural design as buildings components.

2.4. BIM – SDA – SBE Prototype System Development and Monitoring

Asset monitoring and evaluating the performance of a building compared to its simulated performance through sustainable design analysis (SDA), is implemented through building management systems. Automating this process through programming and system optimisation leads to intelligent and dynamic buildings, or smart building environments (SBEs) sufficiently 'smart' to intelligently control building energy consumption, whilst providing a comfort and support for their users (see Fig 5, Zhang et al 2015), with facades for example that can adapt to the environmental conditions both around and within the building, in the real time.

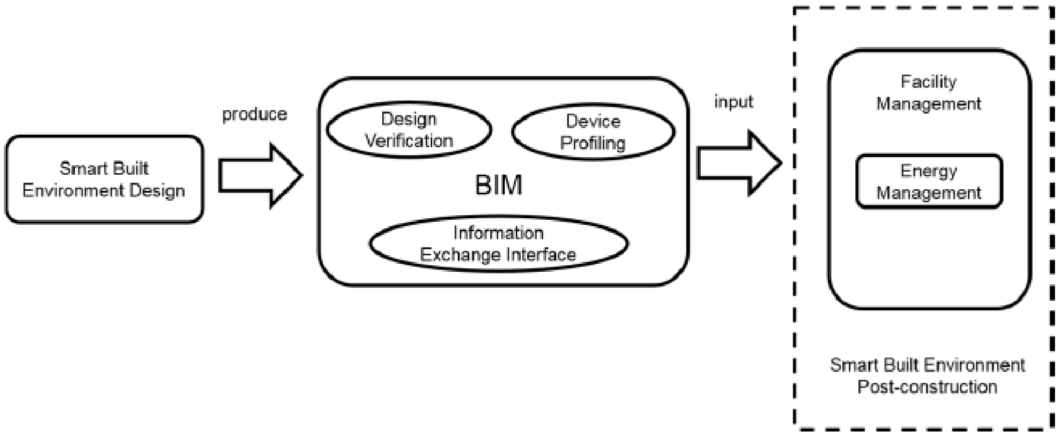

Fig. 5: Concept of BIM and SBE Integration

The advent of machine learning and artificial intelligence means that is possible to analyse the building performance data as real time information accumulates and make intelligent decisions about how building should react to its microclimate. At this point it is almost as if the building could be considered to be "living", as it systematically adapts to the changes in the microclimate conditions, reports issues and requests resources. In the context of shading applications for example, issues would be where building overheats, and resources would be the demand for additional air conditioning or artificial lighting. Access to natural daylight is important for a healthy living environment, therefore it is important the building adapts to keep light within optimum levels and avoids glare. Linking the solar shading to these systems can lead to significant savings (Tzempelikos, 2007). Building performance simulation tools such as the © IES enable designers to evaluate and refine their designs. These simulation methods can be applied to the development of dynamic solar shading systems too, but these are limited when it comes to assessing how the façade should react real time, both from a design and operational perspective. This is where the live data performance monitoring takes over, building on the simulation data, to more intelligently ensures the shading response is appropriate.

Developing a prototype BIM-SDA-SBE application (Ceranic et al. 2018), for this involved connecting an information model based in © Autodesk Revit to sensors in the real world, using © Autodesk Dynamo to evaluate and communicate the data readings. An Arduino Uno Board has been used to take readings of current room conditions, notably temperature using a DHT22 sensor, and light (lux) using a TSL2591 sensor (see Fig 6).

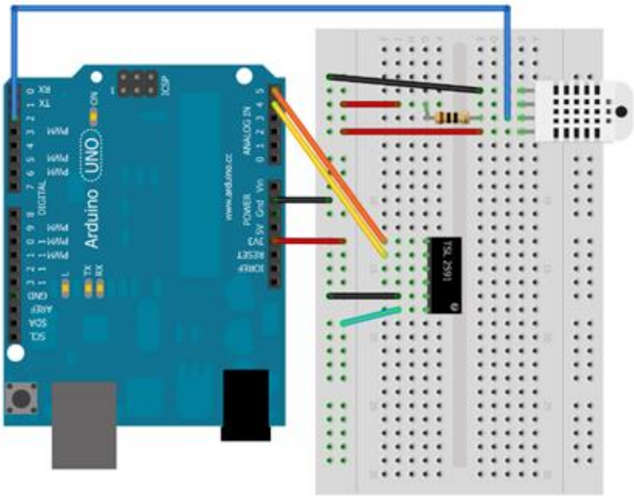

Fig.6 Arduino Board Setup for Real Time Temperature and Light Data. (Bruce J, 2011)

Arduino provides the platform to develop IOT solutions which upload data to cloud platforms such as Azure, leading to building wide applications. However, board uses the programming language C++ which doesn't natively communicate with BIM tools, such as Dynamo which uses Python.

To form the bridge, we used the Dynamo package called Firefly *(*Kensek, K, 2014*.)*, enabling us to bring the data in a useable format. To be able to constantly see the latest data in Dynamo, the periodic running function (6000ms) is used, required as the nodes which read the Arduino output need to be constantly refreshed. When working with large Revit models, the number of calculations often puts a strain on the computation power of the computer. To overcome this the reading of data and determination of shading angle were split into two Dynamo instances running in parallel. The first instance writes the live condition data to a file (see Fig 7), and the second instance uses the link to the Revit model. This mimic the flow of data in typical BMS systems where sub-systems perform different linked functions. In reality, changing the façade more frequently than every 30 minutes would likely result in disturbance for the occupants without major gains in terms of more effective control of heat gains and access to the daylight.

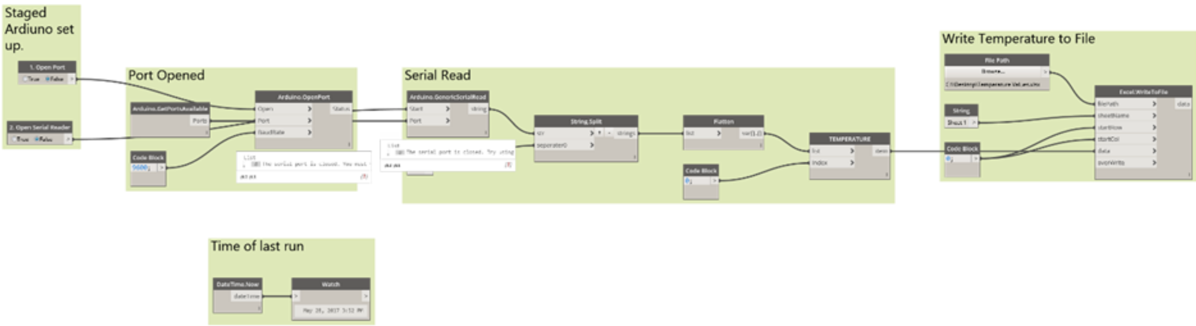

Fig.7 Dynamo Graph showing process for reading data from Arduino Setup. *(*Kensek, K, 2014.*)*

Once the data is available the next step was creating an algorithm for controlling the aperture of shading panels. Early solutions involved applying linear regression to the data to determine the future conditions, building a temperature profile for the conditions like those created during building simulations. The intention with a fully deployed system would be to have a simulated temperature profile which would then be modified to reflect the condition data being reported by the sensors in the real time. Developing temperature and reaction profiles for all seasons and conditions will enable better informed decisions by the evaluating system.

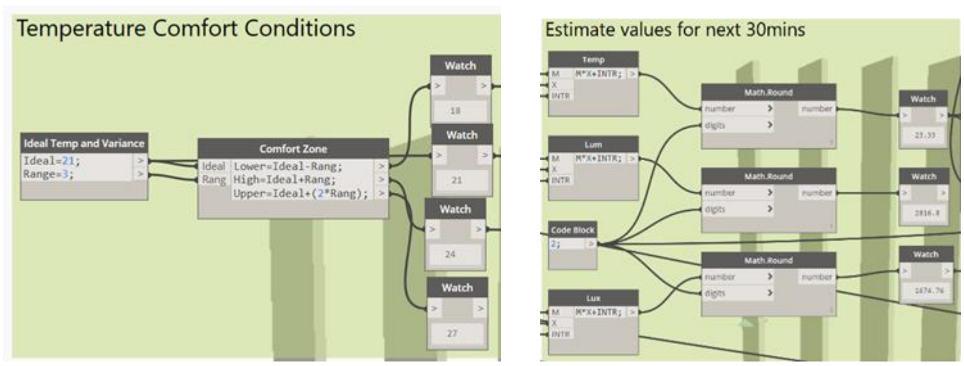

Fig.7 Dynamo graph groups for: Setting the Temperature Comfort Conditions, and Estimating data 30mins ahead through linear regression (Source: Authors)

Temperature results are assessed against the defined comfort conditions (Fig 8). Depending on real time sensors readings in relation to 210C +/-3^{0}C and 300-500 lux conditions in this case, the shading panels opening angle would be adjusted. As part of the linear regression approach, data was cumulatively evaluated in 30 minute groupings to determine the likely temperature and light values 30 minutes later. Figure 8 shows Dynamo visual programming for how these values were then evaluated against the comfort values.

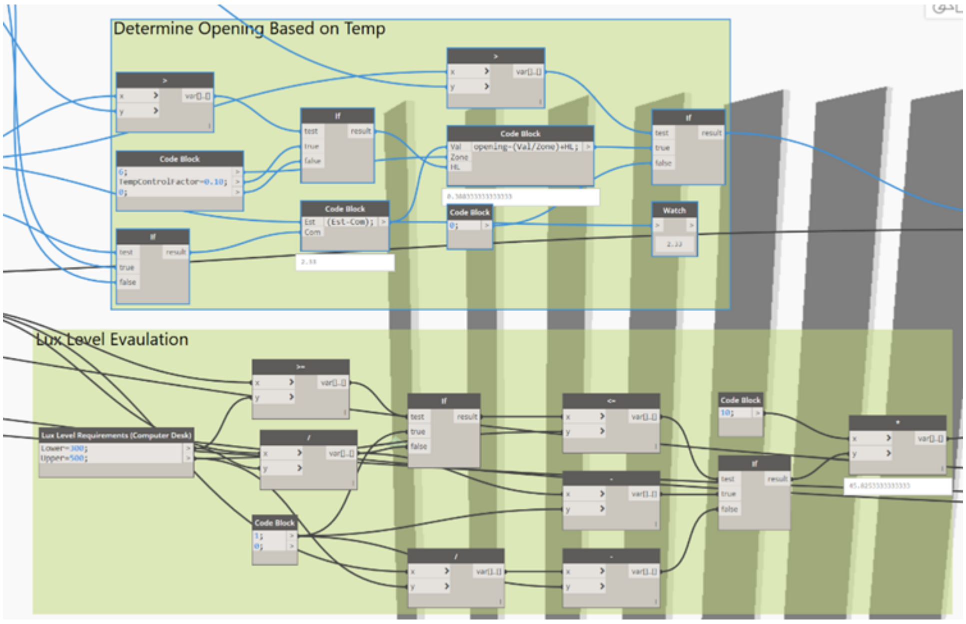

Fig.8 Dynamo Graph Groups evaluating projected data. Top, opening based on Temperature. Bottom, Comparing Data to requirements. (Source: Authors)

One of the key things to keep in mind in this process is that "ideal" conditions may not always meet the requirements of the occupants. To provide the most optimal and sustainable solution, control should be limited, but there are instances where more or less light may be required, or desired temperature is different. Control points are included in the algorithm to simulate where an occupant could make a change.

However, determining the correct aperture of solar shading device needs to rely not only on the indoor comfort data analysis but also the external climate data simulation. For example, incorporating Weather, Sun position and Room Characteristics enables adaptable solutions which react to not only what is typical or predicted, but the actual conditions. In this research, this is achieved by directly linking data monitoring and geometry from a Revit model in real time.

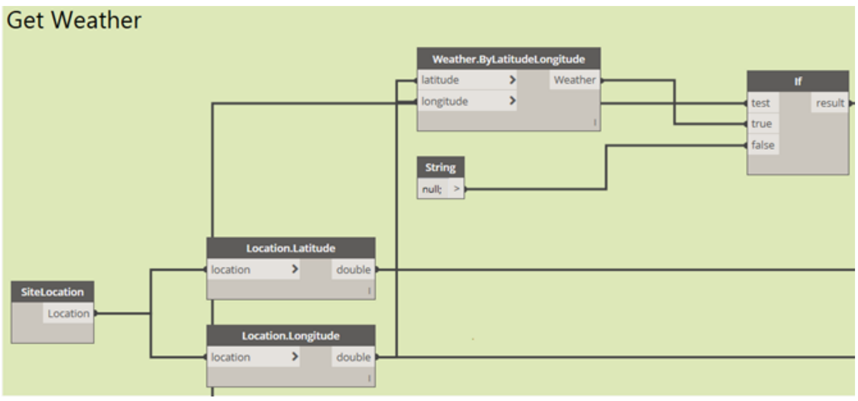

Fig.9 acquiring weather data for given location (Source: Authors)

Solar Analysis was carried out using the 'Ladybird' package in Dynamo, with nodes for generating the position of the sun relative to the position of the building and the weather being visually programmed (Fig 9). The sun Azimuth and Altitude are carried forwards to the solar control nodes as these give the relative position in relation to the elevation (see Fig 12). In this test, a four-storey building was created with a simple linear shading array. Data from the calculations can be visualised on the faces of the building enabling us to evaluate which sections are shading most effectively (see Fig 10).

Fig.10 Image of Test building with Solar Insolation Values visualised (Source: Authors)

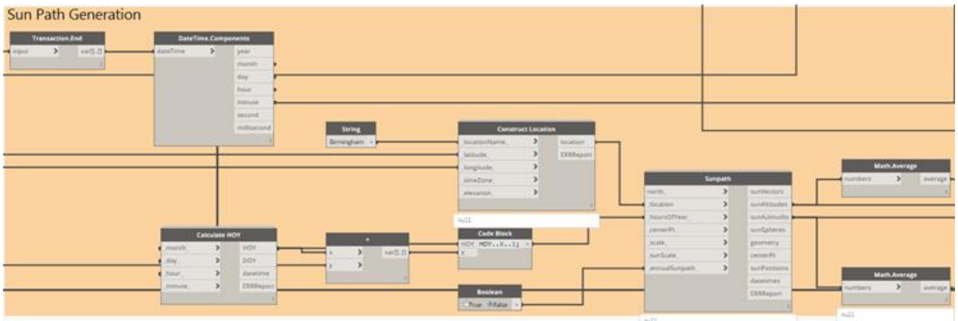

Fig.11 Sun path generation

A custom node (Fig 11) was created to evaluate the azimuth of the Sun and incorporates the ability to optimise how the panels turn in relation to the altitude. This allows the shading angle to be optimised in relation to the sun position

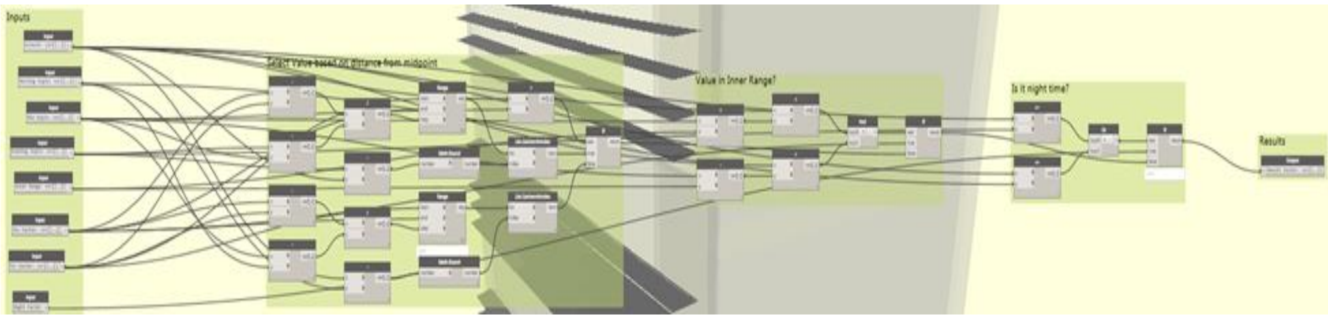

Fig.12 Panel opening optimisation in relation to the sun path

A key part in optimizing and refining the process is accessing how beneficial the shading is for the building, using the package 'Solar Analysis for Dynamo' it was possible to determine the simulated solar insolation (Fig 12). Calculations are run in parallel for when the openings to a room are unshaded, and when the shading at the determined angle is included. Simulated energy levels can be displayed in a coloured grid pattern (See Fig 10), giving vision of where the shading is being more effective.

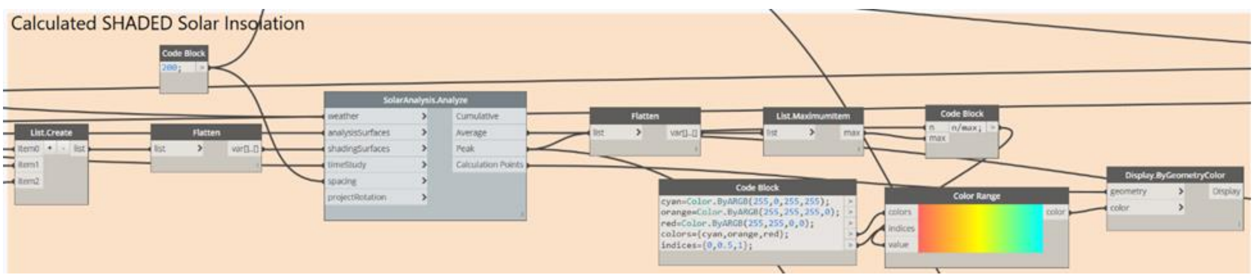

Fig.13 Graph showing calculated data directed to a coloured grid (Fig 10).

This has required the calculation of the net solar gain value. Net Solar Gains through glazing is calculated based on the following Eq (1) below (Szokolay, 2014). This is reflected in the Dynamo graph in Fig 14 where the data is input into the equation. To determine the effect of the shading against an unshaded situation this calculation was carried out with and without the shading array at current specified angle. This gives the heat gains input difference which depending on whether it is positive or negative, will provide the heating or cooling benefit. Recording these values enables us to adjust the control factors in the calculation to better deliver the required temperature reduction.

$$Gain = D_v \theta E \qquad (1)$$
$$Loss = U \Delta T H$$
$$Net = Gain - Loss$$

(Vertical Irradiation) D_V = Wh/m^2
(Solar Gain Factor) $\theta = 0.55$
(Solar 'Efficiency' (Utilisability)) E = 0.9
(U-Value) $U = 1.1$ w/m^{2}K
(Change in Temp) ΔT = Temp 1 – Temp 2
(Hours) H = Time Past

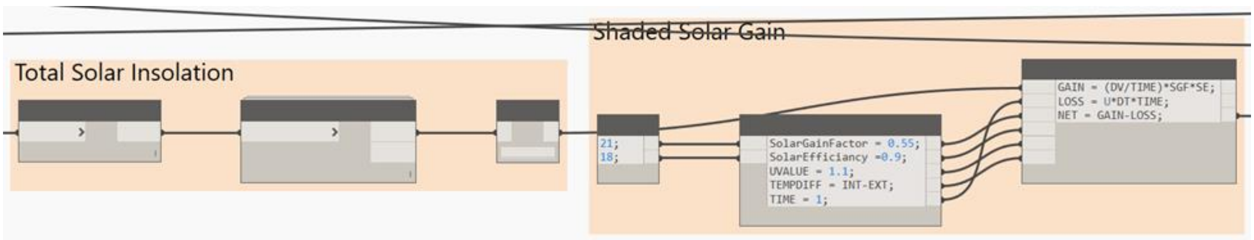

Fig.14 Total Solar Insolation and Solar Gain (Source:Authors

3. Results and Discussion

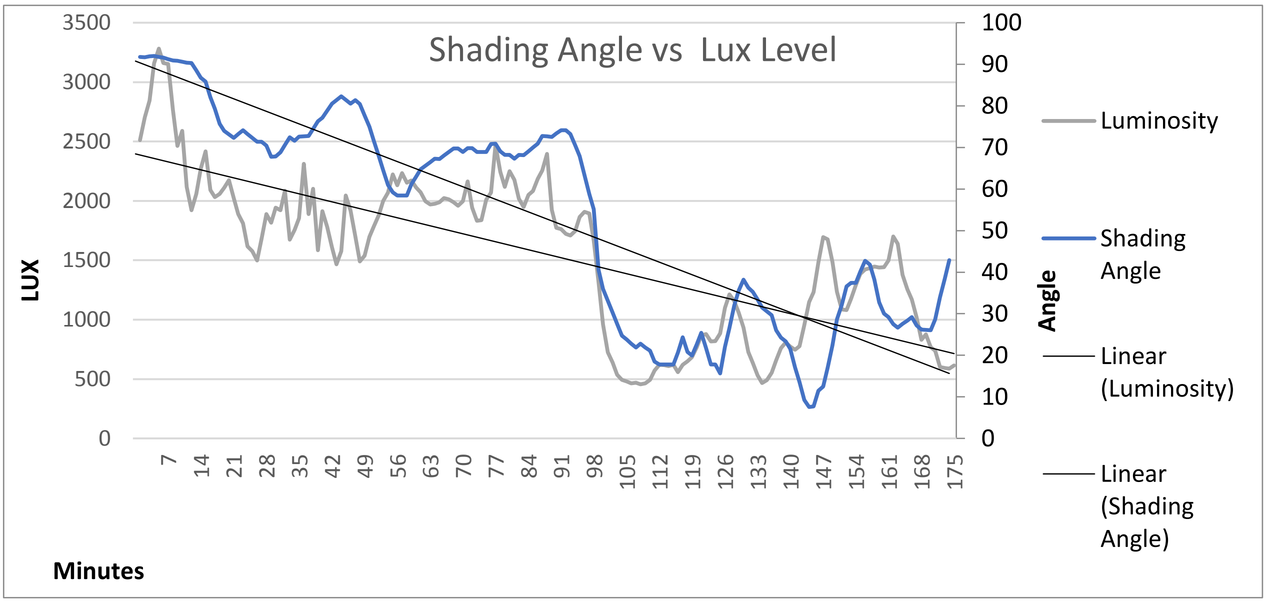

Fig.15. Relationship between Luminosity and Shading Angle, including linear trend lines.

The Fig 15 above shows the data accumulated during the linear regression scenario, comparing the determined shading angle to the lux level being read by the sensor. This links in with the discussed process of azimuth evaluation as varying the angle of shading can maximise the light getting in more effectively. The control point after the lux level evaluation which used the light level to control an angle change was very important to ensure natural light gets to the back of the room, but glare is controlled. The lighting data was compared the defined range of 300-500lux. Being a sunny day, all the recorded values are above this limit, but there was a noteable drop in the lux level between 90-110 minutes, which was related to the sky becoming cloudy and the lux level having a reduced effect on the angle.

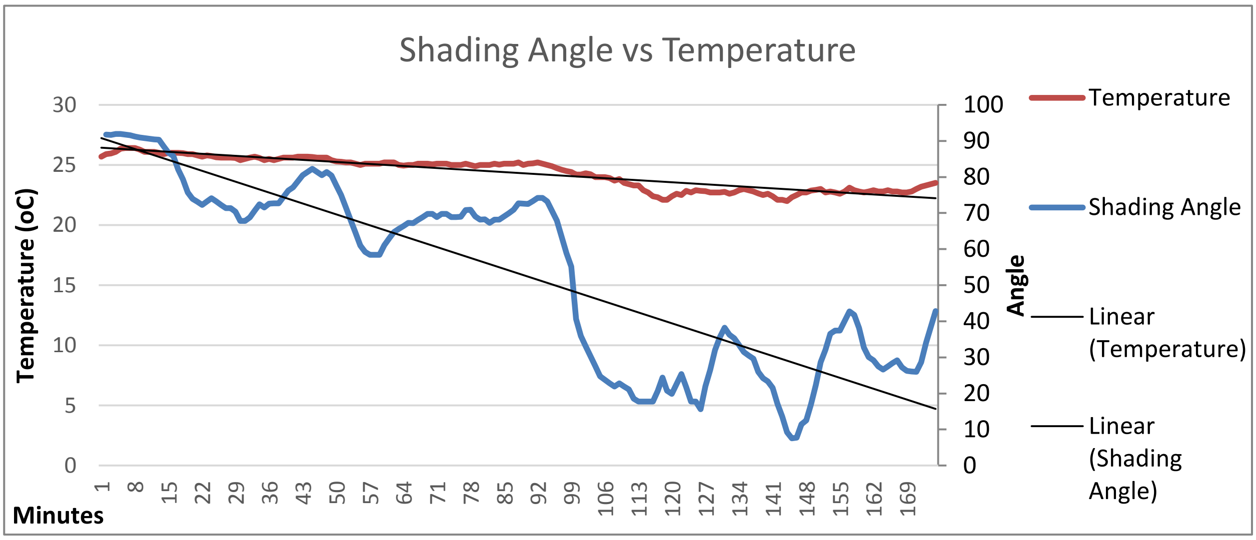

Fig.16. Relationship between Temperature and Shading Angle, including linear trend lines.

The sensor for these tests was placed on a window sill so therefore was more affected by the external change in the conditions and would record consistently high lux level values. Depending on the ratios of window area to floor area and room depth to window head height, different room areas would indeed be receiving less light.

Figure 16 shows the same shading angle data plotted against the temperature. In the linear regression scenario, temperature was the main parameter with the light levels adjusting the shading angle accordingly. The previous graph correlates with the erratic changes in the shading angle which are updated every minute. However, compared to the temperature there is less of a coloration, which could be partly explained by the temperature control factor introduced for temperatures above the upper limit of the comfort zone of 23^{0}C. From 0 to 110 minutes the temperature was above 23^{0}C, which resulted in an extra 10% added by the temperature control factor to the turning angle of shading device to decrease the solar radiation and thus more rapidly prevent overheating.

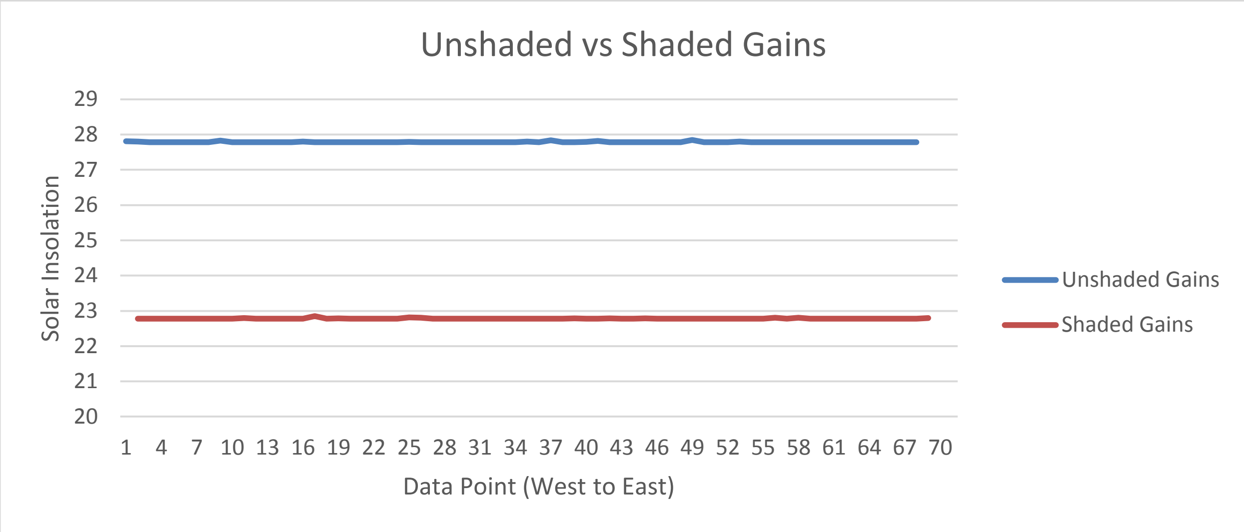

Figure 17. Graph comparing Solar Insolation in Simulated Shaded and Unshaded Conditions

Figure 17 above shows the effectiveness of the shading by comparing shaded and unshaded solutions involving sun, weather and location information. When considered in context of the other heat sources in a room, reducing the overall solar gains can significantly contribute to reduction in overall temperature. In hotter climates where mechanical cooling systems are often employed this should significantly reduce the cooling load required.

4. Conclusions

The research integrates smart façade shading systems and intelligent control of their real time response with a unique and vernacularly sensitive approach to their design through application of shape grammar. Conceived as a generative rule-based concept for the creation and exploration of complex shape composites, shape grammar is founded upon set of simple initial shapes and their predefined composition rules. The developed prototype model adapt in real time via operating upon communication and data-regulation protocols for sensing and processing building performance information, based on the integration of shape grammar, building information modelling (BIM) and system optimisation. The approach of BIM integrated sustainable design analysis (SDA) and open source building energy management system into smart building environments (SBEs) has also been considered, and a conceptual framework for their integration has been developed.

As reported in the research, the first phase of sensor-actuator control has already been developed via bespoke visual programming within the BIM environment that generated virtual sensors with IFC shared parameter field, uniquely defining type of the sensor. Hence virtual objects, in this case smart shading devices, are able to self-actuate and control light transmission properties of the real building component via its real time sensor-actuator connection, based on the results of optimisation algorithm using data from “virtual to real" sensor within the BIM environment (Ceranic et al. 2018).

Integrated BIM system in this research will be extended from the first phase to provide interface for smart objects information exchange through open building energy management system. In the second phase of prototype construction and testing, the BIM integrated building management system will be interrogated on its advanced energy management concept, with both smart objects and system optimisation algorithms deployed.

Potential Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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