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The Role of Geometry for Adaptability: Comparison of Shading Systems and Biological Role Models

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Abstract

Dynamic shading systems represent the majority of realised adaptive façades. It seems that geometrically complex kinetic solutions have increased in recent years, mainly due to the use of parametric design tools and digital production. In most shading systems, however, geometry rarely plays a guiding role in the design. The kinetic mechanisms are confined to linear or planar geometries. Geometry plays an important role in biological organisms, because it is the decisive factor for efficiency and growth. Their growth patterns could provide new insights for dynamic shading designs. For this, spatial morphology criteria for shading systems were identified to obtain criteria directly related to geometry. These were supplemented by criteria on kinetic mechanisms. Then, biological analogies that correlate geometrical structures with adaptability were sought. Using biomimetic methods, particularly from functional morphology, principles in growth patterns were analysed and compared to shading systems. It revealed that the restriction to space, location, and material-inherent properties does not affect the solution diversity, but follows an evolutionary objective: Plants, for example, use ingenious geometrical structures to allow adaptation, mainly over lifetime but also dynamically. Whether these principles can be applied to the design of dynamic shading systems is then discussed. The aim of the paper is to provide impulses for further studies on adaptive shading systems that focus on the innovative use of space with greater flexibility in motion. The overall premise of the paper is to demonstrate the applicability of biomimetic methods for architectural engineering.

Keywords

adaptive facades, shading systems, biomimetics, geometry, growth pattern, kinetic mechanisms, spatial morphology

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1 INTRODUCTION

Dynamic shading systems are of particular interest in the framework of energy efficiency strategies in buildings, because the cooling energy demand raises continuously. The research study 'Cost Efficient Solar Shading Solutions in High Performance Buildings' mentions that "dynamic solar shading leads to mean cooling energy savings of more than 36% when averaged across all glazing types and climate conditions in Europe"; and it could increase to 65-70% for South-West orientated facades in central Europe (Hutchins, 2015). Thus, dynamic shading systems seem to be one of the key measures for drastically decreasing the cooling energy consumption of buildings in Europe. However, recent evaluations show that implemented measures with regard to shadings do not show the desired effect (Hutchins, 2015; Werner, 2016). Since there are few studies on the causes, one can only speculate. One obstacle to effectively operating dynamic shading systems may be the conflict of shading versus visual comfort (view out, use of daylight). This affects the energy consumption of artificial lighting during shading periods. The conflict might be solved by the — currently somewhat neglected — design of shading systems. Conventional products show mainly linear and planar geometries with limited adaptive morphology. Since there are few alternatives that are economically feasible and promise a certain robustness, the potential of the geometry of shading surfaces is yet to be explored.

A closer look at the geometrical characteristics of dynamic shading systems raises questions, two of which are discussed in this paper: What role do geometrical patterns play in current shading systems? And, how do spatial morphology criteria and geometrical forms influence the flexibility of adaptation? Ensuring the best possible functionality and adaptability by using geometrical growth patterns is an essential requirement of biological evolution. The systematic search for analogies in nature could show potentials, particularly for the second question, and enable a design shift away from the neglected geometry to innovative shading geometries. The aim of the paper is to present geometrical patterns of conventional shading systems and draw a link to biological role models that deal with surface optimisation strategies through geometry. The goal is also to illuminate the role of geometrical forms for energy efficiency in this context and to stimulate further studies as to whether spatial designability influences functionality.

The paper begins in Section 2 with a description of the applied methodology to identify various geometrical and functional mechanisms and continues in Section 3 with the categorisation of parameters of shading systems that are linked to spatial morphology, in order to deal with the first question. Section 4 deals with the potentials linked to geometrical forms and functions in nature in order to demonstrate the link between geometry and performance optimisation. It also briefly discusses some principles of the identified geometrical peculiarities in order to determine a possible transfer to dynamic shading systems, which addresses the second question. In the conclusion, a hypothesis is put forward in relation to a re-design strategy for dynamic shading systems based on geometrical patterns, which might overcome the conflict between performance and visual quality.

2 METHODOLOGY

The use of biomimetic methods to identify biological potentials for advanced building design is a trend that has been increasing for several years. Within the field of adaptive façades, optimisation investigations on daylight and shading components by applying biomimetic principles are a central topic. Studies on shape morphing solar shadings by Fiorito et al. (2016) and Pesenti, Masera, Fiorito, & Sauchelli (2015) can be cited as exemplary. While many activities focus on the development of new material composites (Lienhard et al., 2011) or design recommendations in a 'biomimetic' manner (Menges, 2012; Al-Obaidi, Ismail, Hussein, & Abdul, 2017), very few studies are targeted at employing biomimetic methods for re-designing or upgrading existing material and system solutions. This work aims to contribute to this objective by presenting some biomimetic principles for the re-design of geometrical forms for effective dynamic shading systems.

As an initial step towards understanding the role of geometry in the adaptive functionality of shading systems, spatial morphology criteria and kinetic patterns of conventional shading systems were developed. These were then assigned to different shading types in order to classify geometrical and motion-related parameters. In the next step, biological role models, showing geometrical and functional dependencies for the given context, were searched by applying the biomimetic analogy method. To understand the relations between patterns/shape, functions, and behaviour of the role models, a combination of methods from functional morphology, the 'structure-form-(behaviour)-function' model (Sartori, Pal, & Chakrabarti, 2010), and underlying physical laws are applied. It is assumed that patterns and forms in nature follow the laws of physics and thus can be (roughly) explained with mathematical formulae (Cohen, Reich, & Greenberg, 2014). Some conclusions about these relations were drawn in this work. While it is already a complex process to understand and abstract biological 'structure-behaviour-function' relationships, some go even one step further towards identifying generic design patterns (Cohen et al., 2014). This intention is also a motivator for this work, which, so far, is only presented as a hypothesis in this paper.

3 SPATIAL MORPHOLOGY OF SHADING SYSTEMS

Dynamic shading systems represent the majority of adaptive façade systems according to case studies in the COST "Adaptive Façade Network" (COST TU1403, 2018) (Loonen, Trcka, Costola, & Hensen, 2013) (Aelenei, Aelenei, & Vieira, 2016). In addition to the many functions that a dynamic shading system must fulfil with regard to aesthetic, visual, thermal, or structural requirements, its adaptability is the most critical task – more so than with any other façade component. In the design phase, however, shading systems are primarily regarded as an intangible factor for overheating or solar gains evaluation. In energetic building performance evaluations, they are considered as a static value or a range of static values representing worst, best, and standard cases. Their optical properties (transparency, reflectance, emissivity), their influence on daylight quality (daylight transmittance, glare protection, visual quality), and their control strategies are taken into account by global data. The role and performance impact of the specific geometry of an element, as well as its related kinetic patterns, is not considered. Few studies have been found during the literature survey for this work that focus on specific physical characteristics related to the (static) geometry of shading elements in order to enable better energy performance (Fiorito et al., 2016) (Cohen et al., 2014) (Pesenti et al., 2015).

3.1 PARAMETERS FOR SPATIAL MORPHOLOGY

Whenever kinetic movements of façade components occur, certain geometrical and mechanical parameters are taken into account to allow a change of state. Scale, size, and positioning of individual components, as well as the spatial extension and modularity of the system, are some of these parameters that have to be considered when designing adaptive (kinetic) shading systems. Some respective criteria were identified from the analysis of the case studies in COST "Adaptive Façade Network" (COST TU1403, 2018) and further developed for a first draft of spatial and kinetic criteria of adaptive facades (Gosztonyi, 2015). They are summarised as "spatial morphology criteria" (Fig. 1). One such criterion is the 'physical impact', which describes the geometrical appearance of the system, such as planar, linear, or polygonal patterns of the surface, and their changing appearance in the several adaptation states. This also describes the kinetic motion along defined axes (one- or multi-axial). The second criteria, 'repetitive structures', describes the geometrical form itself and the modularity of the elements. While most elements are usually standardised (e.g. strip fins, planar textiles), there is no standard solution for freeform and curved elements. Parametric design considerably supports the development of freeform geometries in order to achieve higher motion flexibility (and performative optimisation) (Barozzi, Lienhard, Zanelli, & Monticelli, 2016). The third criteria, 'spatial versality', is linked to the adaptation mechanisms and its space requirements. Being mounted on guiding rails, hinges, or brackets, shading elements cause a spatial intrusion into the third dimension by folding, wrapping, rolling, and shifting, among others. The mechanisms define the kinetic morphology of the system and determine the coverage pattern of the façade surface. This criteria also describes the space that is needed for the motion, which is critical for the choice of the solution.

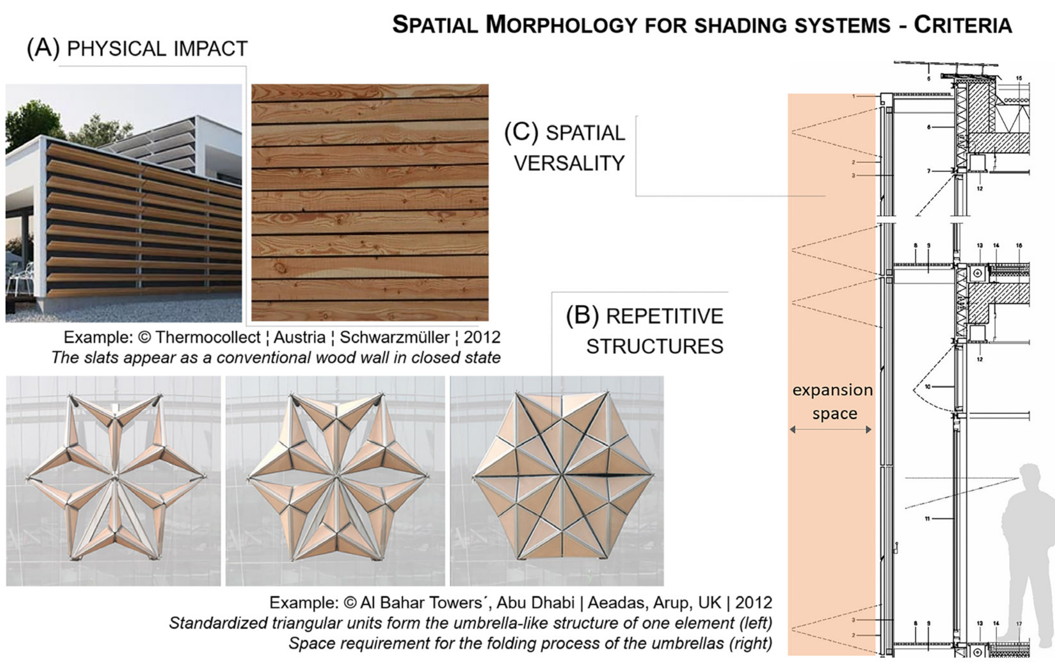


FIG. 1 Spatial morphology parameters for shading systems: (A) 'Physical Impact' deals with the visual kinetic patterns of the shading system in various adaptation states, (B) 'Repetitive structure' with the geometrical properties (size, scale, form of the element), and (C) 'Spatial Versality' with the mechanisms and need of space for motion. These parameters describe the geometrical design of the system *(Images retrieved from Thermocollect, pinterest.com).*

3.2 CATEGORISATION OF SHADING SYSTEMS

To make the geometrical characteristics of conventional shading systems visible, they are categorised according to their assembly types, orientation and motion, material properties, position relative to the façade, and the already mentioned spatial morphology criteria, as shown in Table 1. These parameters are considered to have a direct link to geometrical constraints, although there are other criteria that might indirectly influence the geometry (e.g. comfort requirements, climatic situation, economic constraints).

TYPES		FAÇADE ORIENTATION PREFERENCES	POSITION PREFERENCE	MATERIAL	MOTION	"SPATIAL MORPHOLOGY CRITERIA"		
						Physical impact	**Spatial versality**	**Repetitive structure**
Overhangs, fins, shelfs		South	exterior	all	fixed	static; planar, laminar appearance	horizontal expansion; space need is high	one unit
Brise-soleil, Louvres		East, west	exterior	all	fixed (with moveable or fixed slats)	semi-static; laminar appearance	horizontal; space need is medium to high	one element (repetitive)
Awnings		all	exterior	textile, aluminum, plastic	fixed, moveable	framed, homogenous, planar appearance	horizontal, sloped; space need is medium to high	one unit
Roller, shutters		all	exterior	steel, aluminum, plastics, glass	moveable	laminar, planar appearance	horizontal, vertical; space need is medium to high	one element (repetitive)
Venetian blinds		all	exterior, interstitial, interior	aluminum, metal, wood, glass, plastic, textile	moveable	laminar appearance	horizontal, vertical; space need is minimal	one element (repetitive)
Blinds, screens		all	exterior, interstitial, interior	aluminum, metal, wood, plastic, textile	moveable	planar, circular, polygonal appearance	vertical; space need is minimal	one element (repetitive)
Drapes, cur-tains, blackout screens		all	interior (seldom exterior)	textiles, plastic	moveable	Planar appearance	vertical; no space is need	one unit

TABLE 1 Categorization of conventional shading systems: Identified parameters that provide spatial information or influence on geometry

The constructive characteristics of shading systems are further classified by structural frame types (if not self-supporting), suspension systems (guide rails, hinges, brackets), and kinetic actuators (hydraulic, electric). Positioning relative to the building skin can be either external, internal, or interstitial, whereas the choice defines the spatial expansion bandwidth and performance efficiency. Besides being the best choice for thermal protection, external shading devices provide the most complex geometries and also higher structural and durability requirements, due to the exposure to climatic conditions and aesthetic visibility. Interstitial systems are less demanding in terms of spatial and structural requirements, but cause complicated maintenance requirements when they are moveable. For example, in closed-cavity façades, there is no maintenance option after being installed. Thus, the whole element must be exchanged in case of malfunction.

3.3 KINETIC PATTERNS

Folding, rolling, shifting, etc. are kinetic movements that require certain geometrical arrangements. Shading systems mainly use laminar (fold, flap) or planar (roll, shift) geometries to allow one- or two-dimensional motion. This approach limits the flexibility of shade vs. non-shade areas, and increases the conflict between shading and visual quality tasks. Either one or the other will not perform well, because the surface is shaded either too much or too little in relation to actual needs. Polygonal shapes, on the other hand, allow higher flexibility to cover precisely defined areas and allow the use of planar structures to enable a multi-directional motion (Fig. 2).

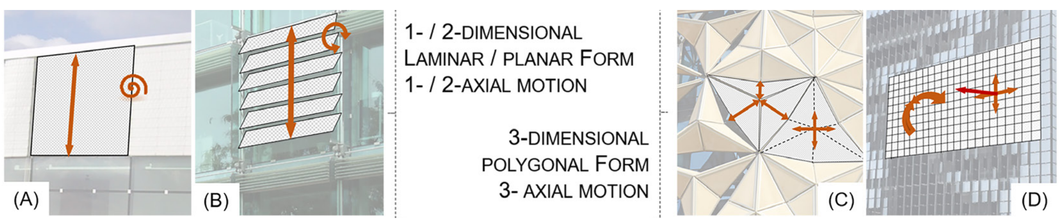


FIG. 2 Geometrical forms and motion types: Planar geometries (A) and laminar geometries (B) move generally in one or two dimensions, using a one- or two-axial mechanism. Three-axial mechanisms need more flexible forms, resulting in polygonal geometries (C) or, at least, rectangular geometries (D) allowing free motion towards three-axial mechanism. *(Images retrieved from flickr.com, pinterest.com, Wikipedia.com).*

This observation suggests that geometrical forms of shading systems seem to be directly related to motion-related criteria. The more flexible the form, the more flexible is the adaptation mechanism, and respectively, the motion pattern, and vice versa. The identified criteria of this observation are summarised in Table 2.

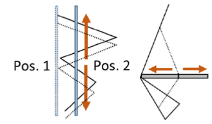
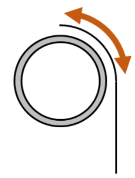
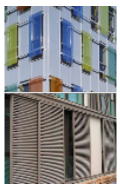
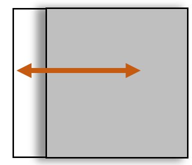
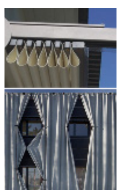
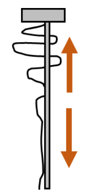
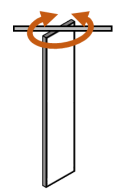
KINETIC MOTION TYPE		GEOMETRICAL FORM COVERAGE OF SPACE	DIRECTION OF MOTION	ADAPTATION SYSTEM	KINETIC MECHANISMS
Fold (e.g. blinds)		planar, laminar form polygonal form linear, grid coverage	2-dimensional 3-dimensional	guiding rails (in various positions), hinges, racks, racks with hydraulic actuator (into z-axis)	
Roll (e.g awnings)		planar form planar coverage	1-dimensional 3-dimensional	brackets, cords, reel	
Shift (e.g. screens)		planar, laminar form polygonal form planar, grid coverage	1-dimensional	guiding rails	
Wrap or lift (e.g. curtains)		planar (flexible) form planar coverage	1- to 2-dimensional	Guiding rails, cords, reel	
Flap (e.g. rotating screens)		planar, laminar form polygonal form linear, grid coverage	2-dimensional	Hinges or brackets, fixed in rails (rotation point)	

TABLE 2 Kinetic motions of shading systems: Selection of most applied motion types and their related criteria for adaptability and geometry

3.4 MOTION INTO THIRD DIMENSION

As mentioned, the complexity of the kinetic mechanisms increases with the complexity of the geometry of the components. The kinetic façade of the Al-Bahr Tower in Abu Dhabi (Attia, 2015) is a representative example of a complex, multi-directional folding mechanism. Inspired by the design of the Arabic mashrabiya, the architect developed origami-like shading "umbrellas" that fold radially via a linear actuator into the third dimension (like the opening of a blossom). Planar PTFE triangle units are steered by hydraulic actuators that "progressively open and close once per day in response to a pre-programmed sequence" (CTBUH, 2018). There are a few examples that use e.g. planar forms, such as the shifting panels of Tessellate™ by the initiative 'Adaptive Building Initiative' of the A. Zahner Company, or the lenses of the Arab World Institute in Paris by Jean Nouvel, to generate hexagonal geometries and patterns. Very few examples allow motion into the third dimension using rectangular geometries, such as e.g. the Wind veil façade project in Gateway Village by Ned

Kahn. Finally, newer solutions liberate themselves from geometrical and kinetic mechanisms and create a motion into the third dimension through their material-inherent properties, such as e.g. the biomimetic "materialsystem HygroScope" designed by Achim Menges and Steffen Reichert or the use of shape-memory alloys (SMAs). All of these examples (also shown in Fig. 3) have a more or less deep impact on the spatial morphology.

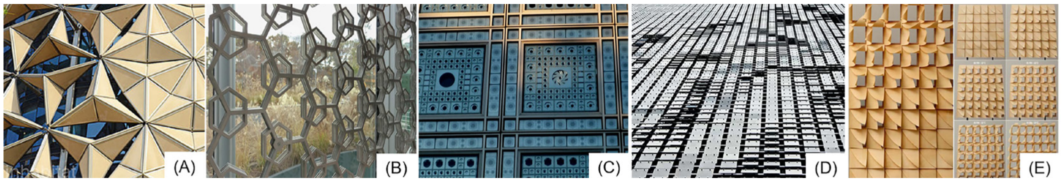


FIG. 3 Grid patterns and kinetic motion in complex systems: (A) hydraulic umbrella shades of Al Bahr Tower fold three-dimensional, (B) the Tesselate ™ concept shifts decorative metal sheets into changing grid patterns, (C) the Institut du Monde Arabe uses a complex photo lenses-like system, (D) the Wind veil façade of Ned Kahn allows wind to play with freely moving metal sheets, and (E) the adaptive biomimetic wood veneer HygroScope from Achim Menges and Steffen Reichert is able to bend automatically according to air humidity change. *(Images retrieved from flickr.com, pinterest.com, Wikipedia.com).*

It might also be of interest to mention that some complex shading geometries are derived from local climatic conditions and related socio-cultural relations: Grid-like, repetitive patterns, such as the mashrabiya in the Islamic culture, are more frequent in regions with higher demands on privacy and higher solar radiation (subtropical, tropical, arid climate) than in cooler climatic zones. Grid-based forms also leave a constant shading pattern due to their frame structure - if it is not fully removeable. The adaptation degree is limited to the element within the grid. This will not be addressed in more detail in this paper. However, it is interesting that these patterns are based on geometrical formulae described by mathematical rules. These are seen as "universal law" in nature (cf. Stankov, 2018).

4 GROWTH GEOMETRIES IN NATURE

According to the works by Thompson (1945), "On Growth and Form", and to more recent publications from Ball (2009), morphological and physiological adaptation has its causality in mathematical problem-solution. It is widely accepted that growth and form developing processes in nature use the laws of physics, whether inanimate or animate bodies. Nature deals with geometrical optimisation to allow growth at any time and any direction. Thus, applying mathematical analysis helps to understand patterns in nature (cp. Turing RD model) (Kondo & Miura, 2010) and might also support the understanding of adaptation mechanisms. It shall be noted that morphological processes in biology are strongly connected to chemical agents and triggers, and influences are difficult to describe solely with mathematical formulae (Morrison, 1987; Ball, 2009).

The basic geometrical form (starting from the molecular level) in biological morphologies is a grid-based shape, based on circular or polygonal units. Together with the basic form, certain growth patterns, such as spiral and sequential growth, allow the biological system to develop and adapt its form. Thus, to understand the adaptation mechanisms of biological organisms, the understanding of their basic geometrical form is necessary. In this section, examples of biological - seemingly static - growth patterns are presented to discuss their growth principles. Although these patterns are not directly associated with kinetic motion, they provide insights into the optimisation of surface geometries for (possible) multi-dimensional adaptability - the goal of kinetic systems.

The second part of this section then presents some kinetic mechanisms in nature and their possible relation to geometrical forms. It should be noted that geometrical forms, growth patterns, and kinetic mechanisms are not necessarily combined in one organism, but may be combined later in a technical solution.

4.1 UNIVERSAL LAW IN NATURE

Two general questions guide the search for biological role models in the context described above: Do geometrical forms play a role in adaptations of biological organisms? And, if so, how do geometrical forms support adaptability?

Shape is crucial for survival and adaptation to local conditions. A good example of this is the eco-geographical rules; these rules state that related species have developed different characteristics depending on the geographical region in order to adapt evolutionarily to the respective climatic conditions. This can affect the body volume (Bergmann's rule) or the relative size of the extremities (Allen's rule). Carl Bergmann suggested that the surface area to body volume ratio of animals correlates directly with the temperature of the region. Mammals and birds in cold regions are usually larger than in warm regions to efficiently maintain or to release body heat (Encyclopaedia Britannica, 2017). Large bodies have a smaller area to volume ratio. The Allen's rule, as a corollary rule to the Bergmann's rule, states that warm-blooded animals in colder regions have shorter protruding body parts relative to their body size than those in warmer regions for the same thermo-regulating reason (Encylopedia.com, 2018). Furthermore, animals living in regions of higher humidity have darker pigmentation than those living in drier regions, which is stated by the Gloger rule (Allaby, 2018). These rules are found in any evolutionary adapted animal, as well as in plants. Although these examples are not dynamic in the sense of the paper, it can be assumed that certain geometrical forms and evolutionary growth patterns also support dynamic adjustments. In the search for these principles, especially in plants (which are unable to move and need to adapt to various local changes and impacts), it has become apparent that particularly geometrical patterns of surfaces facilitate dynamic adaptation. Thus, the analogy search is divided into the investigation of basic geometrical forms (basic growth patterns) and dynamic adaptation mechanisms (kinetic mechanisms).

4.2 BASIC GROWTH PATTERNS IN NATURE

Surface structures and their subsystems are decisively responsible for the control of environmental impact. Their biological patterns, applying geometrical principles such as the Golden Ratio, platonic bodies, and sequential growth, allow differentiated and adaptable morphologies. Figures of pentagonal symmetry and with a high repetitive pattern, in particular, are closely linked to growth. For example, the geometrical arrangements of seeds, branches, leaves or petals using the Golden Ratio allow not only optimisation of the surface area to the solar exposure, as shown in the sunflowers (Fig. 4, A), but also enable kinetic (folding) mechanisms, as shown by the fern leaf (Fig. 4, D).

The Golden Ratio defines herein the geometrical basis for the ability to change, which is enabled by growth patterns such as the Fibonacci sequence. The mathematical connection between the Golden Ratio and the Fibonacci sequence is shown in the Golden Spiral, a proportional growth of φ in a rectangular pentagon (see (C) in Fig. 4), which appears in the static structure of the sunflower blossom and also in the dynamic rolling function of the fern leaf. At first glance, the sunflower does not appear to be a suitable role model for the investigation, since the surface of the sunflower is static and oriented towards maximum solar radiation harvesting in a confined space - an opposite intention to the goal of shading systems. The basic geometrical form, however, allows spatial expansion; the individual seeds of the flower could be multiplied into three-dimensionality within the condensed area due to their polygonal structure. This polygonal surface also corresponds well to the promising examples of complex kinetic shading systems. The aim could be to enlarge the shading surface without consuming more façade surface area – voronoi, tessellation, tangram geometries, and origami patterns could serve as a possible mathematical transfer path. In addition, these geometries allow multi-directional motion, as the fern leaf shows (Fig. 4, D). Shading systems would have more flexibility for individual shading of the surface if this approach were used instead of the conventional one.

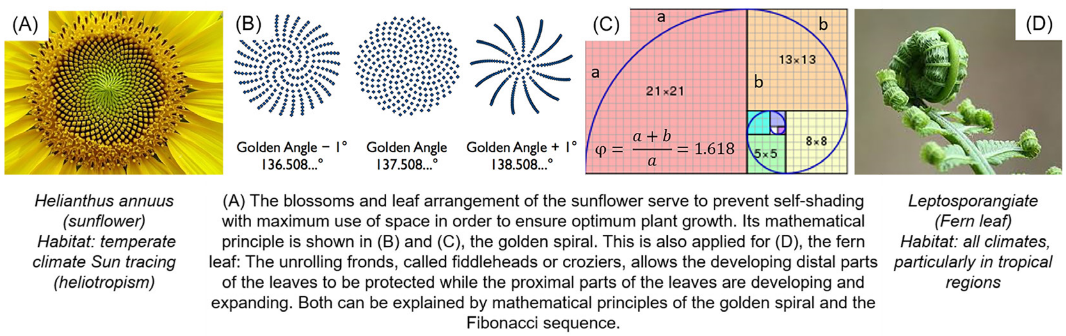
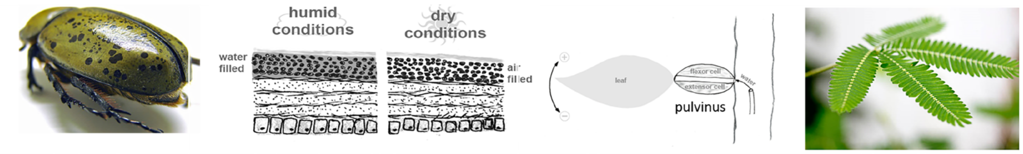


FIG. 4 Biological role models to demonstrate geometrical forms for the optimisation of surfaces and for growth patterns *(Images retrieved from www.greatmathsteachingideas.com, pinterest.com, Wikipedia.com).*

4.3 KINETIC MECHANISMS IN NATURE

The screening of the biological database of the BioSkin project (Gosztonyi, Gruber, Judex, Brychta, & Richter, 2013) revealed that dynamic adaptation and geometrical form optimisation are not always to be found in one role model. For example, adaptive biological organisms that cannot move change their properties ‘passively’ through inherent structure-material characteristics. These can respond dynamically to environmental changes by changing their properties or effects to the environment, e.g. by structural colours, photonic crystals. One example of this kind of adaptation is the *Dynastes beetle* (see left in Fig. 5). Other ‘active’ adaptations are achieved by kinetic mechanism activated through physiological or biophysical processes, such as e.g. folding or curling processes initiated by the Turgor pressure, as applied in the *Mimosa Pudica* (see right in Fig. 5). Kinetic mechanisms are not necessarily related to geometry but influence its morphology. Folding or rolling mechanisms seem to be the most commonly applied adaptation mechanism for shading systems. This also applies for biological role models – insofar as they have been investigated in this work. However, a refined approach must be applied by using detailed abstractions of the search questions and by combining role model functions.



Dynastes Hercules beetle
Habitat: tropical
Structural colour change

Photonic crystal effect is based on the composite of air-filled (n=1 = green) and water-filled (n=1.33 = black) cuticle. Sun light refracts at the chitin-air-interfaces and will be scattered so that the beetle appears differently according to the refraction properties. (S. Gosztonyi, S. Richter: BioSkin)

The pulvinar movement is caused by changes in turgor or hydro-static pressure that leads to contraction or expansion of the leaf tissue. The pulvinus is located at the base of each leaflet. (S. Gosztonyi, S. Richter: BioSkin)

Mimosa Pudica
Habitat: tropical, temperate
Dynamic actuator /osmosis

FIG. 5 Adaptation mechanisms in nature: Dynastes beetle (left) presents a static adaptation by photonic crystals that change its colour according to a changing humidity level. The Mimosa Pudica (right) adapts fast if contact occurs due to the Turgor pressure, an osmotic flow of water through cells *(Images retrieved from Wikipedia. Sketches: S. Gosztonyi, & S. Richter).*

5 CONCLUSION

To answer question one, regarding the role of geometrical patterns in shading systems. Geometrical patterns do not play a major role in conventional shading systems; it seems that the goal of covering the façade area with simple or maximum area-covering forms is of utmost importance. More complex geometrical forms, such as circular or polygonal geometries, are found in vernacular shading systems and have become more popular today due to the digitalisation in design and production. It is assumed that a further development of the polygonal geometries for shading systems could lead to a better interaction between visual comfort and shading function, because the shaded area can be more specifically defined. A follow-up study to this assumption is currently in development.

The second question, about the influence of spatial morphology criteria and geometrical form on the flexibility of adaptation, has not yet been fully answered. Some technical solutions have been studied and it has been proven that more complex geometrical forms are more closely related to a higher flexibility of kinetic motion. In polygonal forms, the kinetic mechanism allows any movement into the third dimension, but simple kinetic mechanisms, such as folding and rolling mechanisms, also allow this expansion. The investigation of biological role models and their adaptation mechanisms supports the hypothesis that polygonal surface geometries (whether at micro or macro level) are the basis for flexible dynamic motions. These geometries enable the multidirectional 'growth' of a system. A possible transfer link between biological principles and a technical solution could be the application of mathematical models, such as the voronoi, tessellation, tangram geometries, and origami patterns. The adaptation patterns in nature have so far only been touched upon and will be a core topic for further studies in order to search for further answers to the second question.

5.1 NEXT STEPS

The purpose of future studies is to continue the above-mentioned investigations and to develop prototypes using certain mathematical models in order to create multi-directional kinetic shading systems that do not use more space but shade more flexibly. Furthermore, the assumption will examined that the visual quality and shading efficiency improve equally if the shaded area of a façade is defined by a grid.

Acknowledgements

The paper is based on earlier work of the author on biomimetic potentials for energy efficiency of façades and the development of design criteria for adaptive façades in a Short-Term Scientific Mission of the COST TU1403 "Adaptive Façade Network". The categorisation of dynamic shading systems was created on the basis of the database of the Working Group 1 in COST TU1403. The author would therefore like to thank the members of the COST TU1403 for the information and framework conditions to carry out this work, as well as the TU Delft Architectural Façades and Products Research Group (AF&P) for the valuable discussions, which were beneficial to the general work related to this topic.

References

Aelenei, D., Aelenei, L., & Vieira, C. P. (2016). Adaptive Façade: concept, applications, research questions . *Energy Procedia 91*, pp.269-275.

Allaby, M. (2018). *Gloger's rule*. Retrieved from Oxford Reference - A Dictionary of Zoology. Retrieved from http://www.oxfordreference.com/view/10.1093/acref/9780199233410.001.0001/acref-9780199233410-e-3667

Al-Obaidi, K. M., Ismail, M. A., Hussein, H., & Abdul, A. M. (2017). Biomimetic building skins: An adaptive approach. *J. Renew. Sustain. Energy Review 79*, pp.1472-1491.

Attia, S. (2015). Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. *Adv Build Skins (Economic Forum, 2015)*, pp.1254 - 1262. doi:10.5339/connect.2017.qgbc.6

Ball, P. (2009). *shapes. Nature's Patterns. A tapestry in Three Parts*. Oxford: Oxford University Press.

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The sustainability of adaptive envelopes: developments of kinetic architecture. *Procedia Engineering 155*, pp.275-284.

Cohen, Y., Reich, Y., & Greenberg, S. (2014). Biomimetics: Structure - Function - Patterns Approach. *J Mech Des 136 (1)*, 111108. doi:10.1115/1.4028169

COST TU1403. (2014-2018). *COST TU1403 – Adaptive Facades Network*. Retrieved 05 28, 2018, from COST TU1403 Adaptive Facades Network: http://tu1403.eu

CTBUH. (2018, 04 07). *Al Bahar Towers - External Automated Shading Systems*. CTBUH Innovation Award 2012. Retrieved from Council on Tall Buildings and Urban Habitat Annual Award. Retrieved from http://www.skyscrapercenter.com/building/id/9129

Encyclopaedia Britannica. (2017, 05 16). *Bergmann's Rule*. Retrieved from Encyclopaedia Britannica. Retrieved from https://www.britannica.com/science/Bergmanns-Rule

Encylopedia.com. (2018, 04 16). *Allen's rule (originally published by Oxford University Press 2004)*. Retrieved from Encylopedia.com - A Dictionary of Ecology. Retrieved from https://www.encyclopedia.com/earth-and-environment/ecology-and-environmentalism/environmental-studies/allens-rule

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *J. Renew. Sustain. Energy Review 55*, pp.863-884.

Gosztonyi, S. (2015). Adaptive Façade – which criteria are needed? *facade 2015 - Computational Optimisation (Proceedings, HS OWL, Detmold)*, pp.84 - 95.

Gosztonyi, S., Gruber, P., Judex, F., Brychta, M., & Richter, S. (2013). *BioSkin - Research potentials for biologically inspired energy efficient façade components and systems*. Vienna: nachhaltig wirtschaften BMVIT.

Hutchins, M. (2015). *High performance dynamic shading solutions for energy efficiency and comfort in buildings*. Executive summary. Abingdon, UK: ES-SO.

Kondo, S., & Miura, T. (2010). Reaction-Diffusion Model as a Framework for Understanding Biological Pattern Formation. Review. *Science 329 (5999)*, pp.1616-1620. doi:10.1126/science.1179047

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinsp. Biomim. 6*, 045001.

Loonen, R., Trcka, M., Costola, D., & Hensen, J. (2013). Climate adaptive building shells: State-of-the-art. *Renewable and Sustainable Energy Reviews*, pp.483-493.

Menges, A. (2012). Biomimetic design processes in architecture: morphogenetic and evolutionary computational design. *Bioinspir. Biomim. 7*, 015003.

Morrison, P. (1987). Reviewed Work: On Growth and Form: Fractal and Non-Fractal Patterns in Physics, edited by H. Eugene Stanley and Nicole Ostrowsky. *Scientific American 256 (1)*, 26-27. Retrieved from http://www.jstor.org/stable/24979292

Pesenti, M., Masera, G., Fiorito, F., & Sauchelli, M. (2015). Kinetic Solar Skin: A Responsive Folding Technique. *Energy Procedia 70*,pp. 661 - 672.

Sartori, J., Pal, U., & Chakrabarti, A. (2010). A methodology for supporting "transfer" in biomimetic design. *Artif. Intell. Eng. Des. Anal. Manuf. 24 (4)*, 483-505. doi:10.1017/S0890060410000351

Stankov, G. (2018, 02 12). *The Universal Law of Nature*. Retrieved from Stankov's universal law press: http://www.stankovuniversallaw.com/the-universal-law-of-nature/

Thompson, D. (1945). *On Growth and Form*. Cambridge University Press: NY.

Werner, S. (2016). European space cooling demands. *Energy (110)*, pp.148 - 156.