Linn Burchert, Lorenzo Guiducci, Petra Gruber & Christiane Sauer in Conversation

Breathing Skins. Plant Leaves and Architecture

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In 2018, Dr. Petra Gruber from the University of Akron, Ohio, and Dr. Lorenzo Guiducci, from the former Berlin Cluster of Excellence *Image – Knowledge – Gestaltung (Bild – Wissen – Gestaltung)*, organized a workshop entitled *Breathing Skins* at Humboldt University.¹ In this context, the group tackled some of the central issues in the relationship between modern and contemporary architecture and the environment: the exchange in buildings between inside and outside, and thermoregulation and insulation. As architect and researcher Colin Porteous pointed out in his 2002 publication *The New Eco-Architecture. Alternatives from the Modern Movement*, it is one of the ironies of contemporary energy efficient and tightly sealed architectural enclosures that they are often accompanied by significant problems regarding air flow, air quality and dampness – a concern that coincides with serious respiratory diseases such as asthma.² This fundamental problem mainly stems from the reliance on HVAC³ systems that profoundly affects the substance of architecture – both in terms of material and spatial concepts – and leads to the use of materials and constructions which are incapable of actively interacting with the surroundings, of absorbing or dissipating heat and moisture. Gruber and Guiducci's project envisioned new approaches to an adaptive, self-regulating architecture. For this, they found inspiration in nature: working with plant leaves as models of respiration they developed novel ideas for future adaptive architectures.⁴ The workshop's underlying methodology – exploring applications of biological concepts with architects and designers – was pursued a year later in a series of lectures and workshops at

1 As summarized in Ariana I. K. S. Rupp/Houette Thibaut/Facundo Gutierrez/Lorenzo Guiducci/Petra Gruber, "Breathing skins workshop: A hands-on investigation of bio-inspired foldable structures for temperature and humidity control in buildings," in: *SPIE* 10965 (= *Bioinspiration, Biomimetics, and Bioreplication IX*), March 2019, pp. 1–18, available at: DOI 10.1117/12.2522089.

2 Colin Porteous, *The New Eco-Architecture. Alternatives from the Modern Movement*, London 2002, pp. 146–163.

3 HVAC = Heating, Ventilation and Air Conditioning.

4 For a general introduction to biomimetics in architecture see: Petra Gruber, *Biomimetics in Architecture. Architecture of Life and Buildings*, Vienna/New York 2011.

the Weißensee School of Art and Design (Weißensee Kunsthochschule Berlin), organized by Prof. Christiane Sauer, in collaboration with the new Cluster of *Excellence Matters of Activity. Image Space Material*. In September 2020 I conducted interviews with the three researchers focusing on plant and skin breathing as a model for architecture, biomimetics, indoor climate and sustainability.

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Linn Burchert (LB): The starting point of your research on *Breathing Skins* was the observation that the geometrical and material properties of plant leaves influence the dissipation of heat and moisture. Based on that knowledge you started thinking about how building façades, roofs and other features might be designed to adapt to environmental influences and changes. An important landmark in thinking about adaptive architectures was certainly former Bauhaus student Siegfried Ebeling's *Space as Membrane (Raum als Membran)* from 1926.⁵ Ebeling's ideas revolve around the question of how to devise an architecture receptive to life-giving environmental forces, while at the same time deflecting or excluding everything harmful to human health. The border between inside and outside is conceptualized as a "Wall Skin" (*Wandhaut*) by Ebeling.⁶ Furthermore, he considered plants as symbols for this new architecture, referring to Johann Wolfgang von Goethe's investigations into the metamorphosis of plants.⁷ While Ebeling focused mainly on radiation, *Breathing Skins* seems to reflect more on airflow channeling and air quality, as well as water management. Do you regard your project as an expansion on or a rethinking of 20th-century architectural utopias?

Lorenzo Guiducci (LG): We can fully agree on Ebeling being a conceptual forerunner of the *Breathing Skins* project. But of course, our experiments, taking place in the year 2018, are grounded on many other works and bodies of knowledge, especially those addressing the role of buildings in multiple contexts – not only as functional enclosures for the inhabitants, but also as part of the cityscape and as contributors to conditions in the urban environment. These more recent works don't see a building's envelope as a barrier to the outside, but more as an interface with the public space.⁸ Therefore, the focus lies no more solely on occupier comfort (an approach that has led to standardized solutions

5 Siegfried Ebeling, *Der Raum als Membran*, Dessau 1926. For an English edition see: Siegfried Ebeling, *Space as Membrane*, ed. Spyros Papapetros, London 2010.

6 Ebeling 1926, p. 8; Ebeling 2010, p. 8.

7 *Ibid.*, p. 21; *Ibid.*, p. 18.

8 Doris Sung, "A new look at building facades as infrastructure," in: *Engineering* 2 (1), 2016, pp. 63–68; Paola Lassandro/Silvia Di Turi, "Façade retrofitting: from ener-

gy efficiency to climate change mitigation," in: *Energy Procedia* 140, pp. 182–193; Michele Zinzi, "Exploring the potentialities of cool facades to improve the thermal response of Mediterranean residential buildings," in: *Solar Energy* 135, 2016, pp. 386–397.

in the thermal management of buildings almost independent of the climate in which the building stands – e.g. HVAC systems); it is shifted to the collective level. For example, façades might be designed to reduce spikes in temperature around a building, thus improving the urban microclimate and benefitting pedestrians. As you hint in your question, a better metaphor for this view is the physical process of air convection (breathing, implying air exchange with the environment), rather than radiation (which may imply ‘action at distance’).

Coming back to the question of architectural utopia: our starting point was rather a technical one and focused on co-opting knowledge from biology (plant thermodynamics) and physics/mechanics (shape-shifting structures) to come up with new concepts and strategies applicable in an architectural context, such as functional façades. But of course, global warming and climate change have made a paradigm shift in how we conceptualize our built environment even more necessary. It is a pressing issue, which probably requires some ‘utopian thinking.’ So, in this sense, *Breathing Skins* possesses something of this.

Petra Gruber (PG): For me personally other references than Ebeling are more important. Especially the group around Frei Otto that dealt with the analogy between biology and architecture, as well as with the analogy between skin and façade.⁹ Among other things, Frei Otto and his colleagues worked on concepts of building construction using membranes and textiles. In conceptualizing the workshop, however, we rather tapped from our own work resources – namely Lorenzo’s work on shape changing and my group’s work on biomimetics, specifically plant leaves and the functionality of evapotranspiration.¹⁰ For instance, in a previous research project, I investigated biological role models for building façades as “Bioskins.” In this project we browsed through biology to envision a future façade system that would be adaptive and negotiate physical responses in terms of heat and humidity management as well as radiation.¹¹ More recent research I have undertaken focuses on “growing architectures.”¹² I also started to collaborate with paper artist Eric Gjerde in a workshop at the Bauhaus Bernau in 2017, which

9 Frei Otto, *Natürliche Konstruktionen. Formen und Konstruktionen in Natur und Technik und Prozesse ihrer Entstehung*, Stuttgart 1982.

10 Petra Gruber/Ariana I.K.S. Rupp, “Investigation of leaf shape and edge design for faster evaporation in biomimetic heat dissipation systems,” in: *SPIE 10593 (=Bioinspiration, Biomimetics, and Bioreplication VIII)*, March 2018, pp. 1–16, available at: DOI 10.1117/12.2302516.

11 Petra Gruber/S. Gosztanyi, “Skin in Architecture. Towards Bioinspired Façades,” in: *WIT Transactions on Ecology and the Environment* 138, 2010, pp. 503–513, available at: <https://www.witpress.com/eliibrary/wit-transactions-on-ecology-and-the-environment/138/21196> (last accessed: 30.9.2020).

12 Thibault Houette/Brian Foresi/Christopher Maurer/Petra Gruber, “Growing Myceliated Façades. Manufacturing and exposing experimental panels in a façade setting,” unpublished conference paper at *Façade Tectonics* conference, Facade Tectonics Institute, Newington, Connecticut, May 2020; Barbara Imhof/Petra Gruber, *Build to Grow – Blending Architecture and Biology*, Basel 2016.

inspired us to look into origami as an opportunity to introduce shape change. Thibaut Houette participated in this workshop, embarking upon his PhD on growing architecture soon after. So all these earlier projects and interests came naturally together with the *Breathing Skins* workshop, where we tried to embed our ideas into an architectural-artistic context.

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LB: Let's go more into detail. You were using plant leaves to develop concepts and practices that would help understand and construct façades as breathing skins. Plant breathing, however, seems to be different from that of mammals in many ways: not only do plants have no organ comparable to lungs, but the result of their breathing could be regarded as the exact opposite of human or animal breathing – at least metaphorically, plants 'inhale' carbon dioxide and breathe out oxygen. As your project title indicates, plants breathe through the skins of their leaves. This skin can be compared to human or animal skin that also serves both as a boundary and a connection between the inside and outside, i.e. the inner organism and the environment. The system of perspiratory glands, pores and epidermis in our skin serve the body's thermal self-regulation.¹³ For instance, moisture is emitted in hot temperatures, cooling the body down. The accompanying loss of water makes us feel dry if we don't provide the body with liquid rapidly. How is plant breathing comparable to animal skin breathing? What are the differences and how can these characteristics be made effective in architecture?

LG: Let me be more specific here. Plants – like all beings with an aerobic metabolism – breathe as we do, consuming oxygen and producing carbon dioxide; it is photosynthesis – which plants do and we cannot – that does the exact opposite. As is widely known, these two processes produce a net positive/negative balance for oxygen/CO₂ respectively.

Coming to the principle that inspired the project title, when we refer to plants' leaves breathing we mean evapotranspiration, that is the combined process of evaporation and transpiration. Evaporation is the phase change of water from liquid to vapor/gas, which needs energy – in form of heat – to occur. Transpiration refers to the loss of water in the form of vapor from the organism to the environment. According to

¹³ See Isabelle Schwarz and Britt Pamela Bannehr's contribution in this volume.

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Fig. 1: Variability of leaf shapes

these definitions, plants' and animals' 'skins' work in the exact same way, 'sweating' to cool down. But the similarities pretty much stop at the bare description of the physical principle.

PG: Exactly, for instance, the skin of plant leaves is usually more or less air- and watertight. What we would call the skin or cuticle is punctuated in exchange areas by pores that lead to a spongy inner tissue where the actual metabolic exchange takes place. For evaporation control, plants can open and close those pores. Also, in contrast to animal breathing, although there is a circadian rhythm to plant exchange processes, there is no process in which one part of the plant is filled with air and then emptied as is the case with lung breathing.

LG: What plants can teach us, however, is an array of different strategies that accompany this principle. First and foremost: the morphology of leaves (Fig. 1). This is a decisive aspect for how heat is dissipated from the leaves.

For example, lobed shapes in general dissipate more heat than convex or roundish ones with the same area since there is more perimeter per unit area available. Another aspect is foliage variability: as sessile organisms, plants have developed a huge variety of adaptations to the climate they live in. The spines in cacti are in fact leaves adapted to arid climates: their shape and ligneous material radically reduces water loss through evaporation; at the same time, the tips help nucleate water droplets from night moisture collecting on the stem surface, contributing to a self-watering mechanism. Leaves grow folded up in a protective leaf bud and unfold only in the mature state; this allows them to be protected against low late-winter temperatures. Many tree species, maple and oak, for example, exhibit sun and shade leaf dimorphism, with a more dissected form in strong sun exposure than when growing in the shade. As can be appreciated by these examples, much plant adaptation to different climates is conveyed by leaf shape. This is not the only strategy that plants deploy (for instance, their chemical composition changes depending on the season), but this is the field where we can draw inspiration for architectural applications such as façade design. Of course, we should not forget that leaves do much more than regulate the plant's temperature. Through transpiration they ensure a negative hydraulic pressure so that water and nutrients are 'sucked up' from the roots through the phloem (i.e. the plant's vascular system); and they synthesize carbohydrates and sugars by photosynthesis. There-

fore, when taking plants and leaves as models for temperature regulation one should avoid ‘over interpretation’: leaves are multifunctional organs and might well not be optimized for thermal regulation alone. As usual in biology, the picture is much more complex than it seems initially.

LB: You’ve been working with origami and paper-cutting kirigami to produce micro-models. What role did the specific and varying materialities of paper and properties such as thickness, texture and geometry play? In what ways do these paper models represent the breathing skins of plants?

PG: In the research on how leaf shape correlates with evaporation efficiency, paper served as a material that can draw in and evaporate water, allowing a crude biomimetic translation of what plant leaves are capable of. It is a material that is already based on fibers – and, interestingly, on cellulose fibers. Thus, there is a direct material connection to biology. It functions like a fleece and possesses a certain porosity. Thus, we could humidify the material and conduct evaporation studies relating to the borders of the forms. The phenomena that we encountered in this research inspired the *Breathing Skins* workshop. The ability to generate folding structures with this material was the other main reason for its choice – the basic idea being to use folding shape changes to modify evaporation rate, and to introduce shape change into structural designs, so creating a dynamic and adaptive system.

LG: We also needed a material that is easy to source, inexpensive, and familiar (even more so since some of the workshop participants were having their first experience of model-making). Paper has a large stiffness to weight ratio, meaning that one can build downscaled models of self-supported structures of a relatively satisfactory rigidity. The other strong argument favoring paper usage arises from the second main inspirational topic of the project: shape-changing surfaces (Fig. 2). This is a vast scientific and technical field to which both origami and kirigami belong (as you mentioned, two ancient decorative arts that use paper), as well as other engineering fields: soft robotics, metamaterials and multistable structures.¹⁴

We selected shape-change principles from this body of applied research and used them as a primer for exploration: using the same

¹⁴ Xin Ning et al., “Assembly of advanced materials into 3D functional structures by methods inspired by origami and kirigami: a review,” in: *Advanced Materials Interfaces* 13 (5), 2018, pp. 1–13, available at: DOI 10.1002/admi.201800284.

basic material as other international research groups just made sense, so participants always started their hands-on work by creating paper prototypes, as a quick initial way of testing whether the moving parts or deformable elements would actuate as expected. Moreover, a book on origami folding techniques was available on the workshop site.¹⁵ As a support for our hands-on work with paper, we also used computer programs to help design crease and/or cut patterns and simulate their folding, or to generate a crease pattern from the 3D shape desired. These computational tools, however, did not inspire the participants as much as making prototypes with real materials. In this regard, I'd like to mention one example as testimony of the very different ideas and prototypes produced with paper and other materials, and of how the different materialities come into play.

Envelop (by Facundo Gutierrez) explores water storage and delayed evaporative release to produce cooling effects on sunny days (Fig. 3). It consists of a geranium leaf-shaped element with two main functional zones: a highly absorbent center (super-absorbent hydrogel-laden textile) for water storage and a larger outer surface for water collection. This apparatus is mounted on a deformable support (built out of paper), resembling the petiole of a geranium leaf. The application setting envisioned is as follows: the leaf element opens on sunny days, while, when it rains, water collects to the absorbent storage core, which thus increases in size and weight. This greater weight pushes down the deformable support (in the figure simulated by the finger), triggering a shape-change effect that leads to the closure of the system, thereby enhancing storage capacity. On warm, sunny days, once the water starts to evaporate, the element opens up again and its broader surfaces assist in evaporative cooling. The concept is proposed as a second skin for façades that can be scaled to a building's size through the repetition of small modules.

This prototype beautifully combines principles of leaf anatomy (the radial symmetry of the geranium leaf), leaf thermodynamics (evaporative cooling) and shape-changing surfaces. It is interesting that no such plant works exactly in this way. Facundo was initially fascinated by the shape and softness of the geranium leaf, which could be easily folded together, though it lacked structural stability. He then added the

15 Paul Jackson, *Von der Fläche zur Form. Falttechniken im Papierdesign*, Bern et al. 2011.

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Fig. 2: An example of the origami shape change principle by Maxie Schneider. Curve-folded bistable panel concept, shape-changing between an open and closed state

Fig. 3: Inspiration, concept and mockups for a paneling element for passive temperature regulation that folds/unfolds autonomously depending on the internally collected water weight

deformable support, producing many iterations of it until he obtained the desired ‘springy’ elastic behavior. I don’t think he would have come up with this solution if he hadn’t worked in paper.

LB: As you mentioned, if leaves serve as an inspiration, your experiments did not necessarily stick to the functionality of plants. Now, how you would describe your overall approach to this biological ‘material’? Thinking of Karl Blossfeldt’s publication *Art Forms in Nature* (*Urformen der Kunst*) from 1928, one method of modeling plants would be to center on aesthetic standards. Blossfeldt regarded plants as artistic-architectural structures that could be reduced to their essential parts – maybe comparable to your choice of working not with entire, living plants, but with plant leaves that eventually wither and fade.¹⁶ In Blossfeldt’s workshops, aesthetically disturbing parts were cut off (for the photograph) or left out (for the drawing), thus producing “biofacts.”¹⁷ What role did aesthetics, structure and simplicity play in your work with leaves and how do operations of precision and/or abstraction in building paper models from plants link to the invisible processes of thermodynamics you were interested in?

LG: That’s surprising, I was not aware of Blossfeldt’s work or of its dogmatic approach to aesthetics (at least, it seems so to me). To “cut off disturbing parts” sounds like confirmation bias to me, a dangerous attitude for anyone who wants to embark in a workshop like *Breathing Skins*, in which scientific evidence played a strong role. I believe – and hope I am right – that aesthetics was not a guiding principle in any of the hands-on explorations. Sure, before the workshop started, we gave participants an assignment: to collect leaves they liked or had recently discovered and were intrigued by. We then asked them to draw the leaves and list the aspects they were interested in. I am sure that at this stage personal taste mattered mostly – all in all “Beauty is in the eye of the beholder.” But as soon as we were through with the lectures on biomimetics, thermodynamics of leaves and shape-changing surfaces, I bet that the general interest shifted and focused on the inner working of leaves. Understanding a leaf in terms of its functions, analyzing it according to the independent layers of thermodynamics, mechanics or chemistry (in short, with the eye of a scientist) requires an abstraction, an effort to eliminate redundancies and filter

16 Judith Elisabeth Weiss, “Sichtbarmachung des Sichtbaren. Karl Blossfeldts Pflanzenurkunden,” in: *Botanik und Ästhetik* (=Annals for History and Philosophy of Biology 22), Göttingen 2017, pp. 237–251, here: 241.

17 Ibid., p. 247.

out irrelevant information. This is indeed a sort of ‘intellectual cutting off,’ but of a rather necessary kind if our aim is to learn new strategies and transfer them to a different field such as architecture. It is important that the relevant information is preserved: we never conceptually segregated leaves from the plant; actually, we were interested in the interaction of plants (through leaves) with their environment, the constraints imposed by the environment, and their adaptation in terms of leaf shape. We provided the necessary knowledge from recent scientific research, so that the majority of the five-day workshop was devoted to the transfer of principles into prototypes through practical work. At this stage hypotheses were tested – can we build a prototype using principles from leaf thermodynamics? Does the prototype work as intended? Eventually there was little time to test the functionality of the prototypes, but thermal images were taken to expose the otherwise invisible thermodynamic behavior.

This doesn’t mean that we were – or are – blind to the beauty of plants. Actually, I would argue that the more the participants learned about leaves, the more they were fascinated by them beyond their appearance. I would rather say that a kind of ‘functional aesthetics’ applies to leaves, since it is remarkable that they play so many roles in plant physiology, while appearing so deceptively simple.

PG: What I find interesting in the reference to Blossfeldt is that he actually did not have any specific research intention – that is, in a scientific sense, at least as far as I know. His photographs, however, published in *Art Forms in Nature*, have a very architectonic feel to them, especially due to the use of classical perspective taken from architectural drawing. This is what makes them so attractive to us as architects. In this way, they produce new information through viewing angles and also through scaling – something that is certainly crucial to Christiane Sauer’s current project on *Scaling Nature*.

Christiane Sauer (CS): Yes, scaling obviously plays a central role when we want to shift from plant systems to architectural concepts. Of course, we cannot simply ‘blow up’ a system; we have to reinterpret it when changing scale and context. As an interpretation always depends on the interpreter’s background – in this case a designer or architect – certain aspects of applications and aesthetics will be preferred over others during the development process. With the Design Studio *Scaling Nature* we let ourselves be inspired by the structure and functionality of

various natural principles, which we of course first had to understand. That is why, from the very beginning, we had researchers from the fields of biomaterials, biology, microbiology and morphology team up with designers and architects to develop new approaches to active materials and surfaces.

LB: This hints to the underlying concept behind your *Breathing Skins* project: that is, biomimetics. Especially since the Renaissance, ideal architecture has been thought of in relation to the ‘symmetry’ and ‘proportion’ of the human body, i.e. to its appearance. It was only later that architects started referring to the organism’s inner processes as a model for architecture – its circulation systems, breathing etc. Today’s organic metaphors as descriptors for architecture mostly stem from the 19th century¹⁸ and refer to buildings as living organisms:¹⁹ “Buildings sweat, age, excrete. And they respire,” as cultural historian Steven Connor wrote.²⁰ How does the idea of architectural façades as breathing skins, inspired by the metabolic and chemical processes in plant leaves, add to the concepts of biomimetics and to a reorientation towards natural principles in architecture and design?

PG: The general idea of comparing a façade with a skin is essentially a biomimetic analogy. We try to translate a functionality that we find in biology into building design, into architecture and the arts. In architecture we are currently experiencing a transition from abstract biomimetic translation to one that actually incorporates living systems, thus moving towards the integration of biology and architecture to create a hybrid, living structures. This interdisciplinary field has gradually developed within the last ten years. There is a shift away from the terminology of biomimetics to “Bio-design” and “Bio-inspired design.” This still includes the well-known concept of biotechnology, which employs biology for technological reasons. These emerging, different fields have become increasingly interconnected and blurred, which is as confusing as it is exciting. I myself was shying away from the concept of “living architecture” because it is hard to define and it is often a mere metaphor to sell ideas and lacks any profound awareness of what life actually is. Still, all these new developments help us to go beyond a mere functional principle in translation and try to take on a more sys-

18 Peter Collins, *Changing Ideals in Modern Architecture, 1750–1950*, London 1971, pp. 149–158; Caroline van Eck, *Organicism in nineteenth-century architecture. An inquiry into its theoretical and philosophical background*, Amsterdam 1994.

19 Also see Oliver A.I. Botar, “Defining Biocentrism,” in: Oliver A.I. Botar/Isabel Wünsche (eds.), *Biocentrism and Modernism*, Abingdon 2011.

20 Steven Connor, “Building Breathing Spaces,” in: Monika Bakke (ed.), *Going Aerial. Air, Art, Architecture*, Maastricht 2006, pp. 118–134, here: p. 138.

temic and integrative idea of what a hybrid between architecture and biology might be.

LB: ‘Bio-inspired’ was the terminology you chose for the *Breathing Skins* workshop. An important process characterizing the relation between your source of inspiration – the actual plant leaves – and your paper models is the method of transposing the 2D-leaves into 3D-shape-changing models. Can this be understood as an approach to develop nature-inspired prototypes that are ‘better’ than nature and how does that relate to the overall issue of heat and moisture dissipation?

LG: As demonstrated by the *Envelop* prototype, there were no a priori constraints on how to make use of the knowledge acquired. What we observed was a tendency to mix and match concepts from leaf thermodynamics with particular origami and kirigami patterns. These patterns allowed for dramatic shape changes that influenced the amount of surface area available for thermodynamic exchange, potentially leading to façades or paneling elements with programmable thermal behavior – more insulating or dissipating, depending on need. In other cases, the shape-changing aspect of the prototype was derived from biology (as in the case of the Venus flytrap). Since full-scale prototypes haven’t been produced and tested, their feasibility and efficiency has not yet been assessed, so it is hard to answer this question. To be ‘better than’ requires comparing two solutions in a similar setting, one from nature, another man-made. Let us take ‘flying’ as an example. An airliner beats any large flying animal in terms of sheer lifting force, speed and range. Is this ‘better than nature’? And what about things of smaller scale – like miniaturized flying objects? You see, it is difficult and also not productive to make such generalizations.

Biomimetics finally leads to a better understanding of the biological world and helps us to select a specific natural principle for a given technical problem in particular external conditions. In this sense it is similar to Frei Otto’s series of experiments on soap film: soap films are minimal surfaces – they minimize total surface area – so he used them as a physical form-finding tool to come up with the lightweight design concepts that minimize material usage. The intrinsic material behavior of soap films is used to generate structural engineering models.

LB: Your project envisions a fundamentally new architecture consisting of flexible membranes, adaptable and shape-changing. Did your project focus mainly on initial experimental thoughts or was actual

practicability crucial to the process, too? While you were working with paper, did you think about new or even common materials that could be employed to realize the prototypes developed during your workshop?

LG: As you say, the workshop was based on theoretical questions, those Ariana Rupp in her PhD thesis work in the Biodesign Lab tried to answer in particular: how does leaf contour influence evaporative cooling? Can we formulate a shape parameter that accurately describes the efficiency of evaporative cooling of any given geometrical shape? How important is it to consider leaves in 3D compared to the usual assumption of a flattened 2D one? These questions investigated before the workshop generated a separate experimental study. In an experimental setup, Ariana used paper cutouts of different shapes but the same surface area soaked in water and then left to evaporate in a controlled climate chamber; during the process the paper cutouts were imaged with a thermal camera to assess local temperature variations and drying rates. Based on her previous work, we knew what could be achieved with no more than paper and water in a lab setting (Fig. 4).

In the *Breathing Skins* workshop, however, no specific scientific questions were articulated in advance. We rather provided the necessary knowledge of the physical principles, some material and a survey of the literature on typical façade design challenges and asked for inventive solutions. This allowed each participant to focus on one specific aspect: air circulation, water storage, water cycling, shading... The hands-on methodology worked as a catalyst for the overall design process. Indeed, the most ‘successful’ projects were those in which computer-generated geometric designs were confined to a minimum and the experimental hands-on phase began early on. And paper was not the only material available: we actually had three basic materials in sheet form that interacted differently with water: paper was considered as a water-conductive element; hydrogel-laden fleece as a water storage/reservoir; polyethylene non-woven fabric as a water repellant layer. Ariana had also worked with other water absorbent materials such as sponge cutouts to obtain enough volumetric expansion upon swelling with water, as well as solid materials, such as fired clay tiles.

LB: Would these novel prototypes you envisage make climate control and air conditioning in the traditional sense obsolete, or can we think of *Breathing Skins* rather as a reform of current climate regula-

Fig. 4: Imaging the evaporative cooling of water-soaked samples with a thermal camera

tion? How is this project situated within recent discussions about passive vs. power-operated buildings?

PG: The project did not directly refer to the wider debate around passive and actively power-operated buildings, as it originally served to explore the design space of functional connections in plant evaporation efficiency and shape. This singular element, however, could indeed inform evaporation devices that could be used in building façades. The introduction of origami and shape change through folding or other principles might also allow us to think about how to add control to passive mechanisms. The overall idea was to have a porous system of a defined shape and then perform a certain shape change, thus ensuring active opportunity to control. We could also think about shape change on a chemical basis, by, for example, changing the porosity of the material in reaction to environmental influences or by implementing active control mechanisms.

Coming back to your question, in my opinion the use of passive systems is completely underrated in contemporary architectural technology. Passively controlled systems are usually capable of functioning within a certain range of exchange requirements and very often this range is not sufficient to generate the comfort that we architects want to achieve for our users. The solution may lie in a combination of such systems. We need to acquire a much better understanding of passive systems and their limitations to find the thresholds where active measures can be introduced that provide sufficient and desired climate control. I think we can be much more analytical and selective: what can be exploited much more are simulations and predictive models – something unprecedented in the history of design.

CS: In the *Cluster Matters of Activity. Image Space Material* we rethink the so-called passive systems that use natural resources like thermal radiation or air humidity for operation as something actually very active. They are called passive because they don't require an applied power source; instead they respond to an environmental stimulus (such as an increase in environmental humidity leading to a shape change in wood or timber, for instance). Seen from the materials perspective it actively performs and responds, if we look into the intrinsic structure and properties. It is an intriguing starting point to reconsider the perception of such systems in the architectural community. The challenge is then to program this 'internal activity' according to our

needs and context, and not consider it as an unwanted byproduct that just happens. In this way, active material systems can gain new interest among architects and designers. Climatic devices should not be hidden behind a wall, in a basement or on the roof. Imagine how enjoyable it would be to design an active origami leaf façade and furthermore even live behind it. I agree it is extremely important to create these design perspectives for *Breathing Skins* in order to pave the way for a new understanding of their potential.

LB: Green roofs, green façades and green walls have been both a future vision and a trend in urban planning over recent years. Does *Breathing Skins* – centering on the characteristics and capacities of plants – provide propositions or even solutions with regards to sustainability and environmental protection? Could this project make air more breathable in urban centers?

PG: As a target, definitely. This was what we were thinking of when we started to research leaf shape and to conceptualize the workshop. At the same time, I think such workshops don't really provide solutions that are directly applicable, but they explore a solution space. With our students we could actually explore several ideas very rapidly and take the promising ones further into research projects and follow up the questions that arose. That's the great power of these workshops: you have this very intense environment and the discussions as well as the inspiration resulting from it. This is how you gain prototypical design ideas that are explored to a certain extent; the question then is how to feed those design ideas into the next stage of research. I really hope that these ideas pave the way for sustainable solutions.

CS: Façade areas as utilizable urban surfaces have been highly underrated. They are thought of as interfaces of potential energetic failure and loss, whereas they should be valued as areas of energetic gain and climate modulation. Extruding a 20-30 meter high building volume from an open plot, its façade surfaces increase the ground surface area many times. These surfaces have the potential for use in energy harvesting or as a climatic or acoustic buffer and can improve an urban environment if innovative material systems such as *Breathing Skins* are applied. It is also important to get industry on board early in the development process if new ideas are to be taken up in the long run. For the implementation of unconventional solutions, such research proposals

function as a beacon. You need a visionary forerunner to get them going and then a conservative market gains trust and follows suit.

LB: As it delves further into research and experiments on biomaterials and architectural scale, the Design Studio *Scaling Nature* at the Weißensee School of Art and Design opens up new perspectives. Within the project you were working on different topics: “Wrinkling,” “Fibers, Muscles and Bones,” and “Growth.” How do these new experiments relate to the idea of a breathing architecture?

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CS: Thinking about a breathing architecture, it will no longer be static, but actively changing, responding and performing. It will not shield the interior from a presumably hostile environment, but interact with external conditions. In *Scaling Nature*, we explored activity embedded into the structure of biological systems, investigating how to transfer this into an architectural design context. The research Cluster *Matters of Activity* provided the ideal basis for this project that brought together disciplines and extended their limits. Over the course of three semesters we looked into the internal activity of different natural materials and phenomena: we explored wrinkling processes in biofilms, skins and leaves, scrutinized the morphological analysis of vertebrate bone and fish cartilage systems, and the principles of growth. A fundamental element found in all biological systems is fiber. Fibers form the basis for structural performance at differing length scales, from tendons and muscles to plant cells and allow for activity and movement of the complete system.

Like material systems in nature, textiles can be programmed to perform on different levels and scales.²¹ For instance, cellulose fiber can be twisted into yarn. When humidified, the material absorbs moisture and swells. As they swell, the twisting fibers cause the yarn to rotate, by its internal structure alone and without the application of any external force. If, at the next level, the yarn is worked into a woven structure, the material’s movement is influenced further by the structural pattern of the overall weave when damp. Based on this, the *Scaling Nature* project *Hydroweave* by Stefanie Eichler and Juni Neyenhuys explores how textile modules made from paper yarn react to moisture (Fig. 5–7): they bend and roll. As a surface, they open up with increasing humidity and close again when drying. Parameters such as yarn diameter, twist

21 Peter Fratzl/Richard Weinkamer, “Nature’s hierarchical materials,” in: *Progress in Materials Science* 52 (8), 2007, pp. 1263–1334, available at: <https://doi.org/10.1016/j.pmatsci.2007.06.001>.

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Fig. 5-6: *Hydroweave*, Stefanie Eichler/Juni Neyenhuys, MoA Design Studio *Scaling Nature*/Christiane Sauer, Weißensee School of Art and Design

Fig. 7: *Hydroweave*, Stefanie Eichler/Juni Neyenhuys, MoA
Design Studio *Scaling Nature*/Christiane Sauer, Weißensee
School of Art and Design

direction, warp thread density and binding pattern were explored to achieve the desired results. By choosing the right parameters the overall performance and movement of the modules can be precisely programmed. The resulting surface could be applied as a 'breathing' skin that opens up to let the humidity evaporate or become a climatic device in hot conditions that would allow a cooling breeze to enter a room during a shower of rain. Nature is an infinite reservoir and inspiration for novel solutions. The key lies in structure and geometry.

LG: I agree with Christiane's view of breathing architecture as something that is in exchange with the external environment. A breathing architecture should be conceived as an open system. It defies, or rather questions, the idea of a building made of segregated functional units. In this regard biological materials are interesting systems to observe since they usually fulfill multiple needs. Mostly, they are open systems, optimized for a variety of tasks rather than a single one, and have evolved in processes that have lasted for million years under strict constraints, such as access to a limited number of chemical elements. This usually results in inventive and often unexpected solutions that differ from traditional engineering. Although in the *Scaling Nature* Design Studio we embark on a different theme each semester, these general concepts always recur. As the physical principles and biological models are presented first, the design projects developed by students begin from an unusual starting point and take unexpected turns. Since the focus is on materials, experiments and hands-on explorations are not too dissimilar from the lab work of a scientist: in the process they might stumble upon something interesting – a mechanical behavior or optical effect – that may become a spin-off scientific project in itself. I personally find the mix of concepts and methods from science, architecture and design very rewarding. It is a perfect milieu in which new ideas – be it for science, engineering or architecture – can be arrived at.

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