Pneumatic structures in motion

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Abstract

The possibility of movement is a fundamental property in nature. Movement means adaptability and flexibility which protects creatures better from their own ruin and destruction, but also ensures preeminence over other species. Adaptability and flexibility allow responding to different requirement in an equal way. This should be desirable for artificial structures, but still only few existing buildings are able to react to changing environmental influences, like the few stadiums with a flexible roof or the few movable bridges. Usually our buildings and structures are passive. They are built to satisfy more or less only one function. But due to massive chances in society, this does not meet today's multifunctional requirements and it is not economical any more. Resulting out of this, new tasks for engineering evoke. But it makes only sense, if the structures are light, not only concerning appearance but also in weight. Heavy structures do not only need more energy to be put into motion, but also the possible movement will be justified less accurate. Vice versa the use of high-capacity materials leads to new possibilities in design, construction and movement. Pneumatic constructions fulfill this claim of light weight and if ETFE-Films are used they allow transparency as well as ultraviolet rays passes them. This makes them quite desirable for indoor swimming pools – the marketing likes to advertise that guest get a tan even in winter. But certainly in summer, outdoor swimming has to be available; therefore a multifunctional roof is needed.

1. Introduction

The capability of movement is a typical property of natural structures. Movement means adaptability and flexibility which protects creatures from their own ruin and destruction, but also ensures dominance over other species. Adaptability and flexibility allow responding to changing requirements in an adequate way. This should also be desirable for artificial structures, but still only few existing buildings are able to react to changing environmental influences, like the few stadiums with a flexible roof or the few movable bridges.

Usually our buildings and structures are passive. They are built to satisfy more or less only one function [1]. But due to massive changes in society, this does not meet today's frequent requirements for multi-functionality and may lead to uneconomical solutions. Resulting out of this, new tasks for engineering arise. But these only make sense, if the structures are light, not only concerning their appearance but also their weight. Heavy structures do not only need more energy to be pushed into motion, but also the possible movement will be less accurate. Further the use of high-capacity light-weight materials leads to new possibilities in design, construction and movement.

Pneumatic structures fulfill these requirements of light-weight and movability. The lighter the structure the easier is the possibility of movement. If the proper movement can also be achieved by air pressure, i.e. if costly and heavy mechanisms can be avoided, literally light-weight movements can be achieved.

2. Principle of pneumatic structures

If a pressure difference occurs separated by a membrane, i.e. a flexible foil, easy to bend and with comparable high tensile strength, the membrane buckles to the side of the lower pressure and is stabilized laminary. The result is a single-curved or double-curved surface, shaped by the pressure difference and the cutting of the foil.

In structural engineering pneumatic structures are known as air-inflated and air-supported structures. While in air-supported structures the air pressure is applied between the surface and the ground, in air-inflated structures the air pressure is enclosed in a cushion or a tube. The development of pneumatic structures started with air-supported structures, but they have to deal with several problems like a big air volume and a comparable low air pressure, which is restricted because the interior is used by people. On the other side the air-inflated structures enclose the pressure with a continuous membrane so that the interior is decoupled from the pressure. In the term of discovering the adaptive potential of pneumatic structures this paper will focus on air-inflated structures as there will be a smaller amount of air volume which has to be handled, a wider range of different air pressures are possible and no compatibility with human restrictions (i.e. influence of air pressure to the human body) is necessary.

Applied as structural elements the air inflated cushions or tubes have to carry external loads as well as they have to carry their own lightness. The structural task designing a pneumatic structure is to find an optimal interaction between the inner air pressure, the stresses in the membrane and the external loads. The aim is that different load cases as snow or wind do not significantly change the initial form.

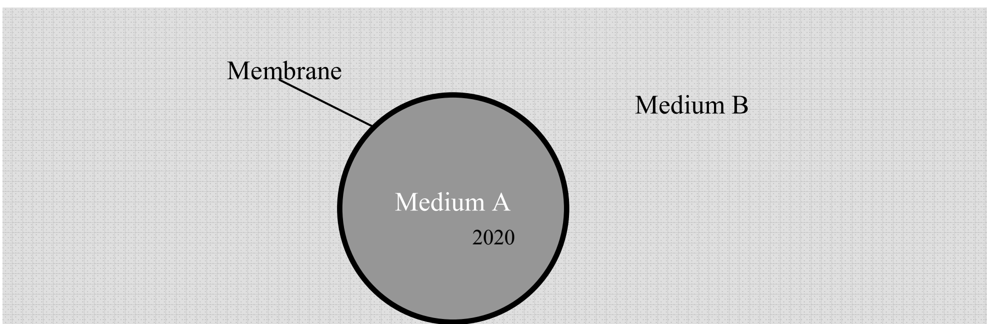

Figure 1: Principle of pneumatic structures: pressure A ≠ pressure B

2.1 The need of pressure control

Hence the pressure difference is both, the stabilizing and the form giving parameter, the structure is behaving very sensible to changes. Therefore the pressure has to be controlled carefully; generally this is done by a pressure control unit responding in real-time to the changing conditions or a possible leak in the system. Figure 2 shows the interaction between all relevant parameters [2].

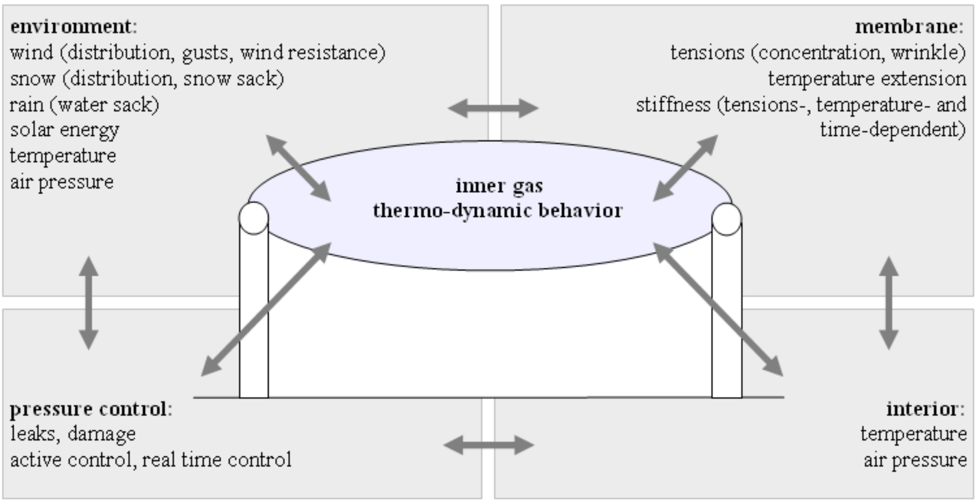

Figure 2: Pneumatic structures and their interaction with the environment

The physical relation between pressure, temperature and volume is described by the changes of state of a system, which is divided into three special cases: isobar, isothermal and isochoric. An air-inflated membrane structure is best described with the isochoric state, since the shape and therefore the volume of the cushion should remain unchanged. The temperature as a control parameter does not work, because the incoming air neither is cooled down nor heated, so the environmental conditions are essential.

The general equation of state is:

$$p \cdot V = m \cdot R \cdot T \qquad \text{with: } V = \text{const.} \tag{1}$$
$$T = \text{not controllable}$$
$$R = \text{const.}$$

Therefore the inner pressure is only controllable by manipulating the gas mass. The diagram (Figure 3) shows the variation of the inner gas mass to attain two different system pressures. Starting from point 1 with constant volume the pressure and the inner gas mass of the system varies in order to reach point 2. From point 2 to point 3 the volume is increasing by changing the gas mass with constant internal pressure. In both cases the temperature is changing but not as a controlled parameter.

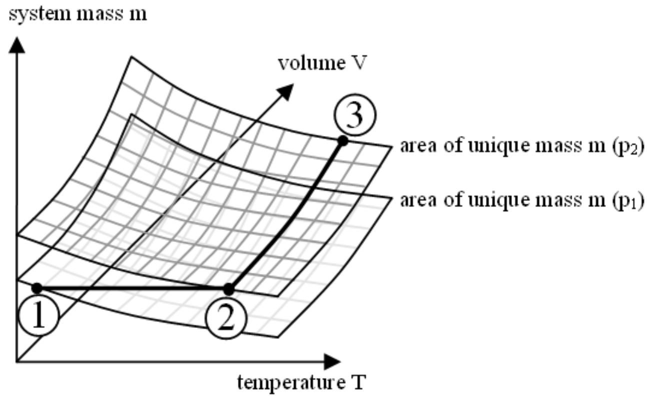

Figure 3: Variation of the system mass

3. Movement of pneumatic structures

Due to their lightness air-inflated structures are predestined to be put into movement. First projects are realized as parallel sliding foil cushions (figure 4), but they are not utilizing the whole potential of the pneumatic structures.

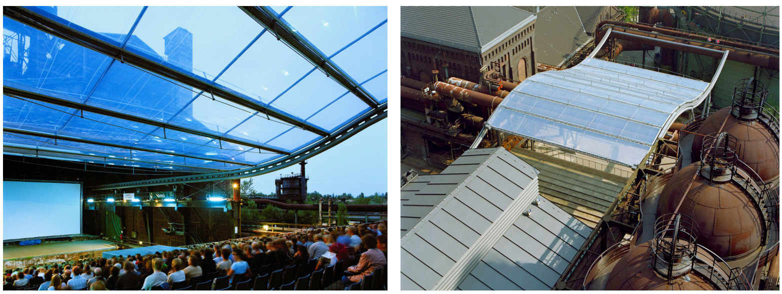

Figure 4: Pneumatic roof, Duisburg, Germany, Schlaich Bergermann and Partner, 2003

3.1 The benefit of pressure control

The above-mentioned need for regulation of pneumatic structures leads to the idea of implementing the desired motion by the same mechanism without any extra motors or cable pulls. Ideas like this go back to designs from the 70ths: T.Oki & Associates designed in 1969/70 a flexible umbrella with a central movement (figure 5).

Figure 5: adaptive construction with stabilization by in- and deflating, T.Oki & Associates, 1969/70

This idea of pneumatic movement can complete the morphology of Frei Otto for possible movements (figure 6). Here Frei Otto described the different directions of moment [3], depending on the type of construction. Working with convertible pneumatic structures it is most reasonable to extend the existing morphology. For air-inflated pneumatic structures three directions of movements can be added: parallel, central and circular. The proposed prototype will focus on the parallel movement.

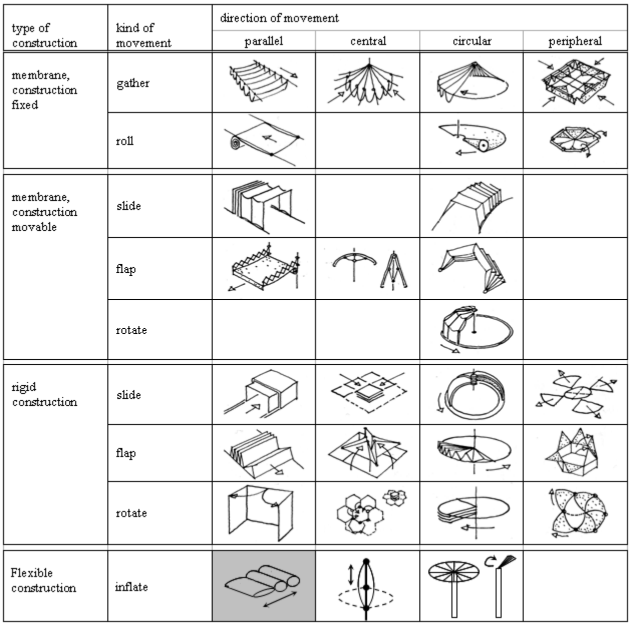

Figure 6: morphology of Frei Otto with addition grey deposited

This basic principle for such a parallel movement will be the change of an eye shaped cushion to a circle shaped cushion. Figure 7 and 8 show the geometrical parameters of a double layered cushion. To explain the principle of the pneumatic movement the geometric interrelations will be explained.

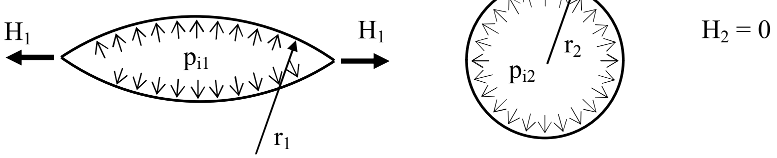

Figure 7: Dependencies of the holding force H depending and the form

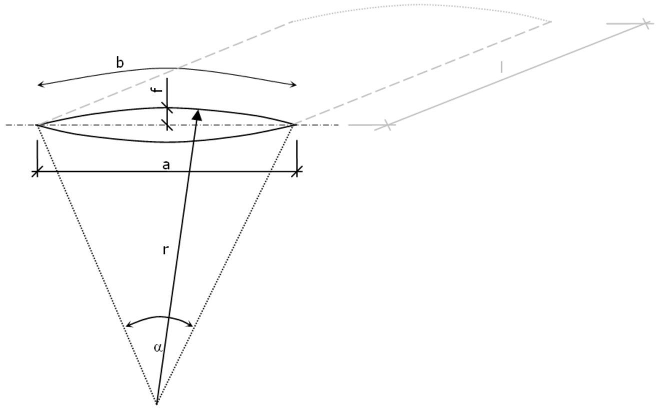

Figure 8: geometry of a cushion with notations

In all phases of the movement the circumference of the form remains the same. That means for a minimum volume near zero (both membranes are parallel to each other; f = 0 | R = ∞):

$$a_{max} = b \tag{2}$$

$$U = 2 \cdot b \tag{3}$$

With this circumference the area of the maximal possible circle is easy to calculate:

$$r_{min} = \frac{U}{2 \cdot \pi} \tag{4}$$

$$A_{max} = \pi \cdot r_{min}^{2} \tag{5}$$

So the relation between a and r_{min} is:

$$r_{min} = \frac{2 \cdot a_{max}}{2 \cdot \pi} = \frac{a_{max}}{\pi} = \frac{b}{\pi} \tag{6}$$

The maximum movement possible is described by:

$$\Delta a = a_{max} - 2 \cdot r_{min} = a_{max} - 2 \cdot \frac{a_{max}}{\pi} = b - 2 \cdot \frac{b}{\pi} \tag{7}$$

Evaluating the equation (7) the maximum of Δa_{max} = 36.34 %. This should be clarified by an example.

Two folios fixed on the long sides by edge beams, and horizontal movable on the others is the basic system (the spring is just for convergence). To get an initial tension into the membrane a horizontal force H pulls against the inner pressure (figure 9).

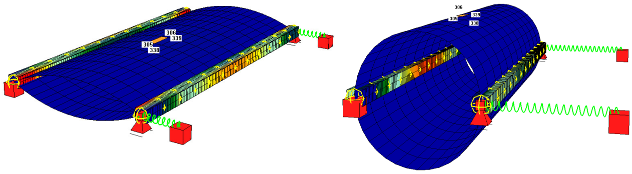

Figure 9: basic and moved system

The horizontal holding force H is:

$$H = \frac{q \cdot a^2}{8 \cdot f} \qquad \text{with: } q = 0.5\ \text{kN/m}^2 \tag{8}$$

$$= \frac{0.5 \cdot 6.0^2}{8 \cdot 0.75} \quad \frac{[\text{kN/m}^2] \cdot \text{m}^2}{\text{m}} \qquad a = 6.0\ \text{m}$$

$$= 3.0\ \text{kN/m} \qquad f = 0.75\ \text{m}$$

This force will be multiplied with the length l and divided by both bearings (two foils → double force). For this situation the system is in balance. By discharging the force H to zero the foils will describe in the end the desired circle. Figure 10 describes the correlation between holding force, inner stress and elongation.

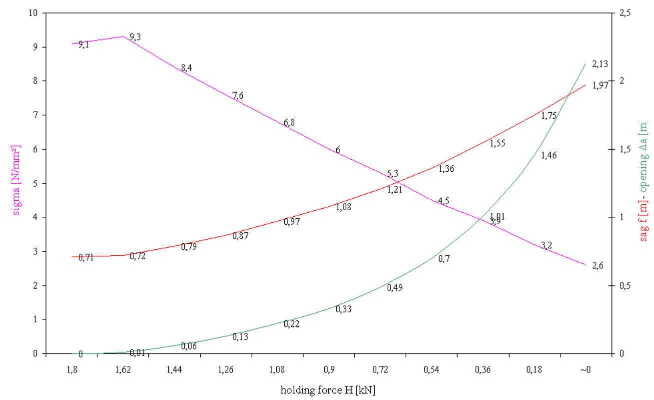

Figure 10: variation of the horizontal force H and change of the depending geometric values

It can be seen that the membrane tension decreases almost linear. The sag change is reverse linearly dependent and the opening follows a root function.

$$f = \frac{q \cdot a^2}{8 \cdot H} \qquad \rightarrow f \sim \frac{1}{H} \tag{9}$$

$$\Delta a = \sqrt{\frac{H \cdot 8 \cdot f}{q}} \qquad \rightarrow l \sim \sqrt{H} \qquad (10)$$

Through a succession of several cushions a large opening is possible, with the maximum relative movement still about 36 % of the elongated length (figure 11).

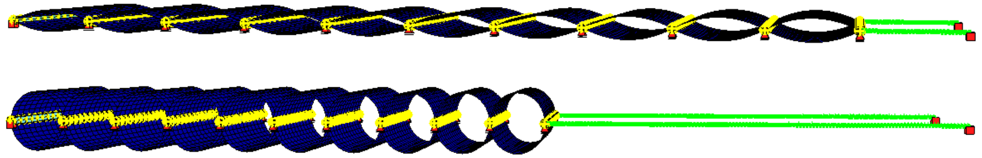

Figure 11: serial connection of elementary elements

Theoretically the proposed system is possible for an infinitely long barrel shell, ignoring the problem of the boundary situation at the small side. But a pneumatic structure is finite and needs to be closed on all edges.

3.2 The boundary problem

At a first glance the boundary problem seems to be a geometrical problem: how to transfer an elliptical shape into a circle? But as the circumference of both cross sections are the same, the area differs. Any physical solution requires an ideal elastic material which allows this geometrical transformation. But as we want to apply this transformation in the context of a pneumatic structure, this ideal elastic material would not only deform geometrically, but also would deform under the inner air pressure. And in any case, such an ideal elastic material does not exist at all. Both solutions shown in figure 12 are not working because of the high desired deformations of the smaller sized boundary.

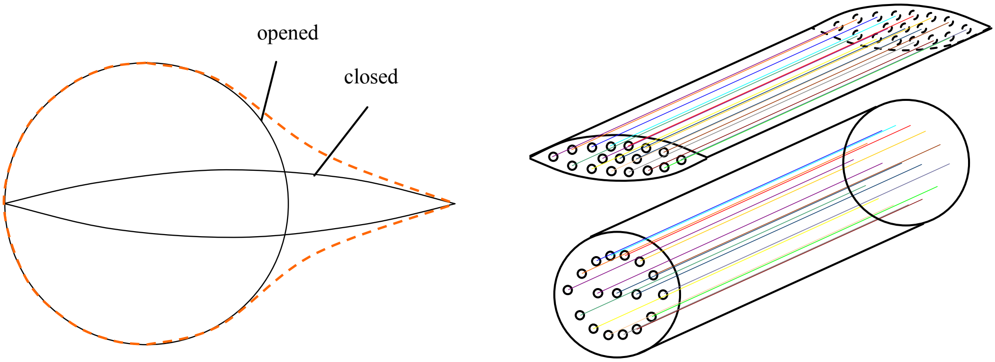

Figure 12: geometric change of the small side boundary

3.3 The boundary solution

The ultimate solution was finally found by avoiding the geometrical boundary problem: this means the transformation of the geometrical two-dimensional problem into the third dimension. Thereby the form of the edges themselves remains unchanged. The short edges are twisted against each other. The flat rectangle will be transferred into a spatial shape (figure 13). This kind of movement requires ideal rotation of the corners.

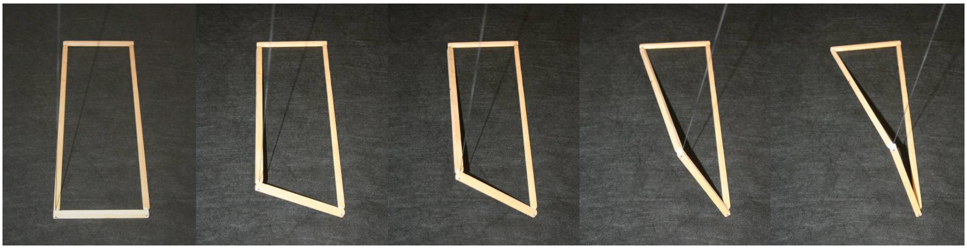

Figure 13: twisting the rectangle

The edges of the rectangle are rotated around their center like a seesaw, and are not moved in their absolute position, which theoretically corresponds to no kinetic energy. In the middle occurs the desired circle, but to the front ends still exists the eye formed cushion. Only the middle section can perform deformation work.

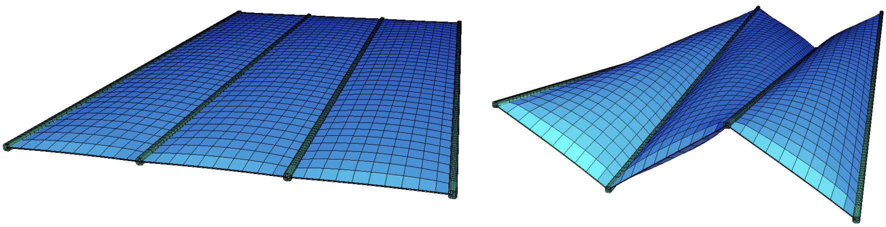

Figure 14: geometry for several connected cushions

3.4 Prototype

The geometrical description of the movement of the vertexes is following an arc of circle around the midpoint of each edge. The short edges are rotated with an angle of 45°. The rotation of the long edges is defined by their hinged connection to the short edges. The first prototype has been realized, but needs further improvement and is only presented in rough outline to give an impression. So for this first stage of the research the behavior of the cushion itself was neglected.

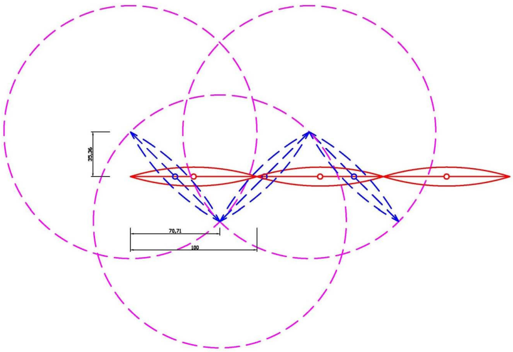

Figure 15: geometry of vertexes

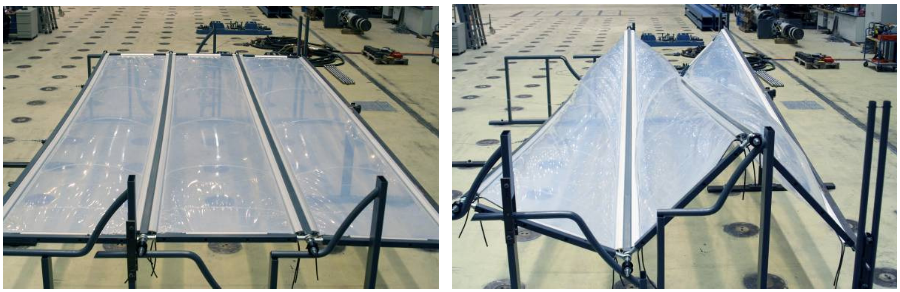

Figure 16: impressions of the prototype

4. Vision and Summary

The use of pneumatic structures allows very light-weight primary structures as well as secondary structures (i.e. the cushions). The force needed to move this weight is less in comparison to normal, just movable-made structures ($F = m \cdot a$). Today multifunctional structures are required for sport and culture events. Foil cushions are especially attractive for swimming pools for all-season use. A fast and easy adaptation of a structure to multiply weather conditions enhances the benefit of the whole investment.

This paper presents the idea and the concept to utilize the full potential of pneumatic structures. This can be achieved with cushions as actual actuators of the desired movements. But further research is necessary to develop this principle in all structural elements and functionality, i.e. material behaviour and structural detailing.

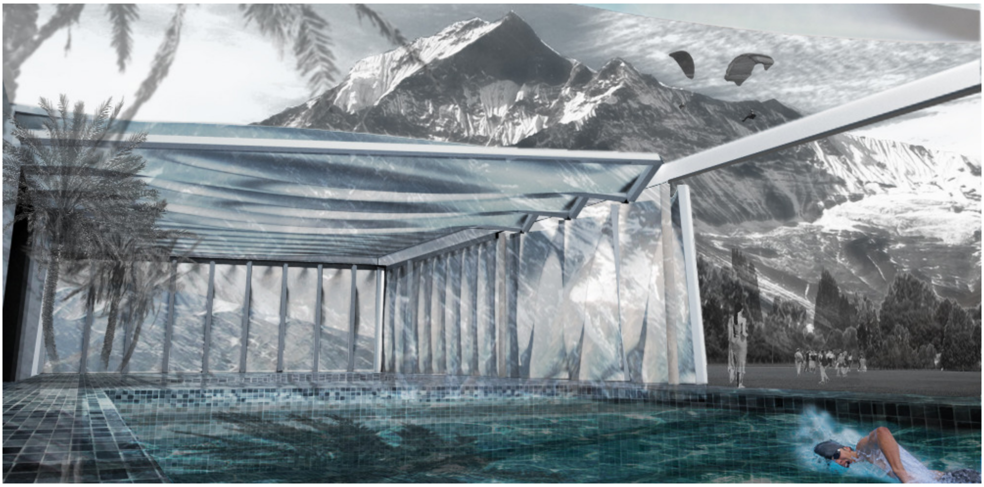

Figure 17: Visualization of the described pneus in motion for roof and façade (kPlan AG).

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