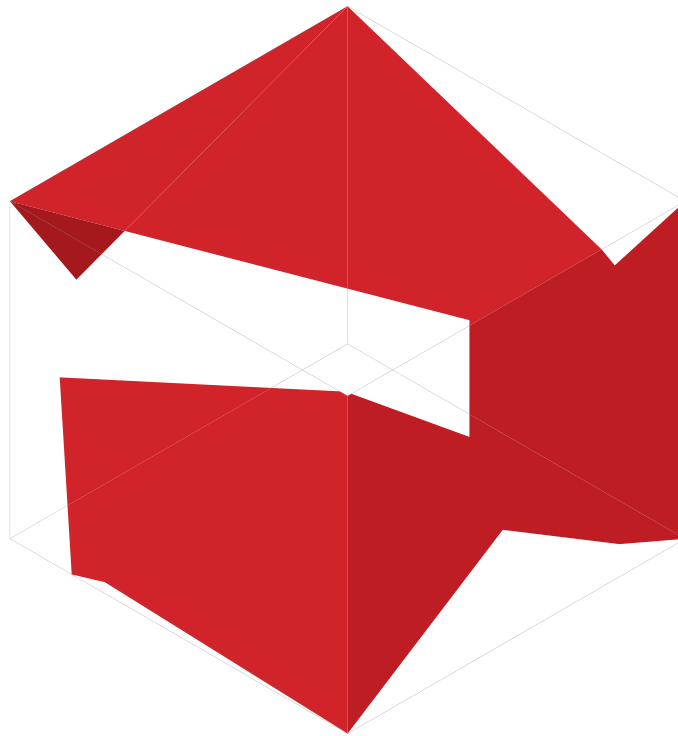


Studies in Material Thinking



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Volume 07 Where Art, Technology and Design Meet

Towards Interconnectivity: Appropriation of Responsive Minimum Energy Structures in an Architectural Context

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Abstract: This paper introduces Reef, a design-led investigation into the conceptualisation and materialisation of a self-actuated ceiling surface. Relying on minimum energy structures as an example of an adaptive element, Reef showcases an approach in which the design of shape-changing structures through an efficient 2D-manufacturing process leads to the creation of highly poetic and complex adaptive structures, while suggesting new opportunities for the implementation of electro-active polymer technologies in a domestic context. By reporting on the conceptualisation, the design and realisation of the installation Reef, this paper will highlight future possibilities for architectural materialisation questioning how responsive technologies can encourage the design of a home more interconnected with its surrounding environment.

Keywords: material tale, electro-active polymers, adaptive minimum energy structures, responsive architecture, temporal tectonics, domestic environment

STUDIES IN MATERIAL THINKING

<http://www.materialthinking.org>

ISSN: 1177-6234

Auckland University of Technology

First published in April 2007, Auckland, New Zealand.

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STUDIES IN MATERIAL THINKING is a peer-reviewed research journal supported by an International Editorial Advisory Group and is listed in the Australian ERA 2012 Journal List (Excellence in Research for Australia).

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Figure 1. Reef, a self-actuated ceiling based on responsive minimum energy structures.



Figure 2. Implementation of Reef into a domestic context.



Introduction

The idea of home as an actuated environment emerged with the implementation of environmental technologies such as heating, ventilation and air-conditioning, where a variety of sensing-actuation systems took over the management of the interior's thermal, luminous and acoustic environment. Transforming the home into a space primarily conditioned by technology, these developments have reinforced the perception of the interior as a hermetic entity, more and more independent from its surroundings (Addington 2009). However, as we start to realise the consequences of our ability to engineer the world, the urge to investigate new roles and new narratives for technology becomes more and more pressing. With the emergence of smart materials arises the potential to apprehend the building as a zone of exchange rather than a zone of delineation, as a dynamic environment, not only connected, but actually fundamentally interconnected with its surroundings (Addington, Schodek, 2005, pp.4-8). *Reef* asks how dielectric elastomer can be appropriated so as to re-establish a relationship of interconnectivity between nature, the home and its inhabitants.

Material Tale for Dielectric Elastomers

The dielectric elastomers derive their motion from simple physical principles; hence they are open to many variations in their realisation. They are lightweight, highly responsive and controllable, and can be manufactured from natural and renewable materials. Therefore, dielectric elastomers - a specific family of electro-active polymers - present particularly interesting qualities for the materialisation of a dynamic environment.

The essential principle of dielectric elastomers as actuators can best be described as electrical charge storage in a soft capacitor. When electrical charges (+ and -) are stored in a soft capacitor, they will strongly attract each other and some of these forces will deform the dielectric elastomer. Since the dielectric elastomer is soft, the deformations can be more than 10%. As actuators, these materials change shape and structure without an internal sliding motion when electrically stimulated. Compared to more traditional actuators, they stand out for their complete silence, gracious motion and high adaptability. It is this rare combination of features which has inspired the *Reef* exploration.

While they hold a lot of promises as energy-harvesters or as sensing building skins (Laflamme, Kollosche et al. 2011), architectural applications involving electro-active polymers remain uncommon. Probes such as *Sun Trap* or *Homeostatic Façade* illustrating concepts for dynamic shading systems attest of the complexity to engage these materials on an architectural scale (Ilek 2009, Decker Yeadon 2010). They also reveal the technology-driven focus through which electro-active polymers' applications are currently investigated. The novelty of these materials as commercial products coupled with the need for basic research in this field, can partly explain this phenomenon. However, beyond the practical and the technological, these new materials offer new poetical and cultural opportunities which remain under-explored. In this context *Reef* develops a 'material tale', a term originally coined by Anthony Dunne, defined in this context, an embodied narrative mixes fragments of reality and fiction, questioning and mediating how to appropriate these new technologies in our everyday (Dunne, 2005, p.123). Inspired from the world of sailing, where the word reef evokes the part of a sail that can be tied or rolled up to make it smaller in a strong wind, *Reef* works as a metaphor of control and actuation. Between sky and earth, the installation embodies a space of mediation where, like sails and subject to the unpredictability and variations of airflow, *Reef's* components fold and unfold as they sense wind. However, while the sail satisfies a specific need - controlling the speed and stability of the ship - *Reef* stands outside of the primacy of function, exploring the poetics of a world of negotiation.

Reef As A System

Reef is a journey across scale, from the exchange of electrons, to the design of responsive components and their coordination as a dynamic environment. This material tale is embodied in a life-scale ceiling installation, where an archipelago of electro-active modules constantly re-designs the interior's landscape as they change shape according to the exterior.

A series of minimum energy structures hanging from a supporting panel compose the central element of this aerial canopy. The digitally crafted surface gathers both active and passive components in three sizes. These components are shaped according to the principle



of energy minimisation (Kofod, Paajanen et al, 2006). A sheet of rubber activated by pre-stretching, is fixed to a flexible plastic frame. The frame bends and flexes into a complex shape in response to the activated rubber.

Interestingly, due to the dielectric elastomer effect, the minimum energy of the rubber can be directly modified to produce responsive structures. This is achieved by claspings the rubber sheet between two electrically conducting stretchable sheets, in effect creating an electrical capacitor for storage of electrical energy. All in all, there are three energy domains in play: the elastic energy stored in the rubber; the one stored in the frame and the electrical energy stored in the electrical capacitor. These simple scientific principles leave a very large design space open for exploration (Mossé, Kofod, 2011).

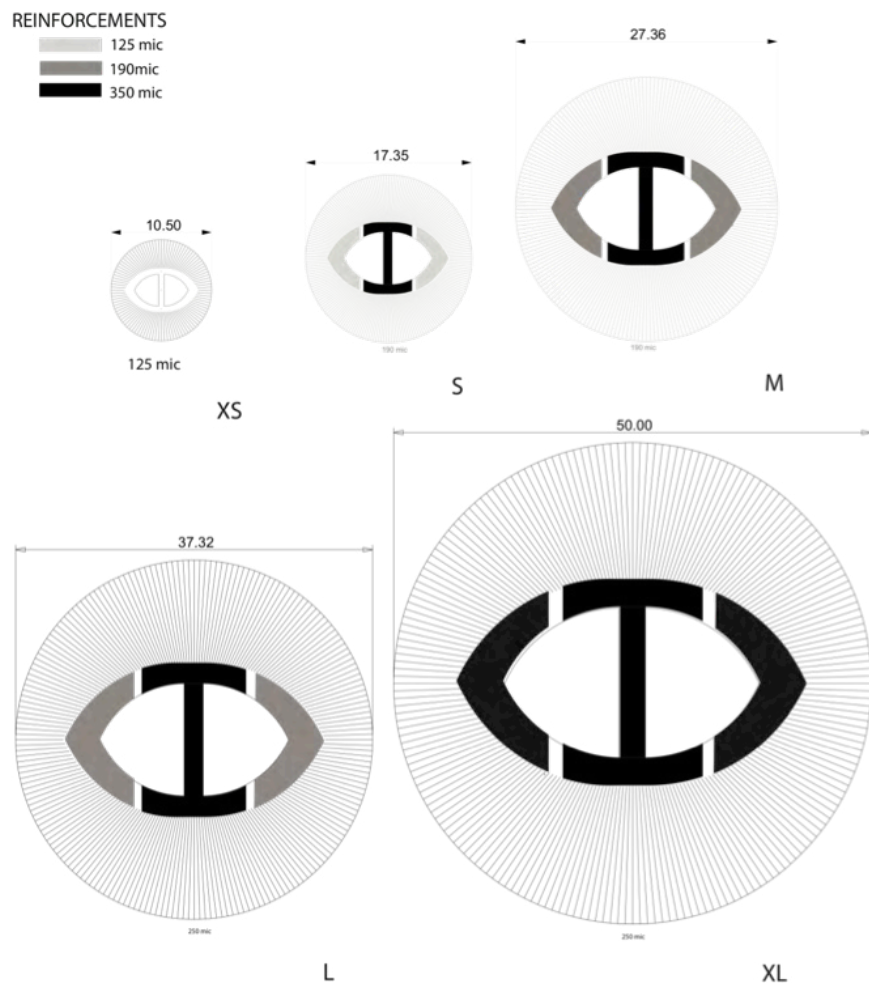


Figure 3. Reef's components sizes and their material composition.

Within *Reef*, efforts were concentrated towards the choreography of single elements into time and space. The spatial organisation of these elements as a cloud was privileged to reinforce the aerial character of the installation. As a domestic canopy, it defines a porous membrane that blurs the boundary between the interior and the exterior by reintroducing natural patterns of time within the home. Designed to react to wind fluctuations, this responsive field is defined



by two types of behaviours. While passive modules shiver in response to indoor airstream, active components linked to a wind sensor are programmed to open and close gradually, following the pulse of the wind.

Engineering Design

The wish for successful exploitation of dielectric elastomer material's responsiveness into meaningful, perceptible, and dynamic morphologies, made it necessary to develop an approach where the visual design and the construction of each kinetic piece became an integral component of the engineering design (Berzowska, Mainstone et al, 2007).

Controlling the erratic behaviour of the pre-stretched elastomer in order to insure optimized morphology and actuation is at the core of this process. This was explored intuitively by building and testing variations of similar structures in order to find the appropriate balance between the frame's flexibility, geometry and the elastomer tension. Digital tools addressed the level of precision required for adjustments across the multiple design scales involved in the project.



Figure 4. Actuation test, *Reef's* XS component.

Reef's components were laser-cut from Mylar® polyester film between 125 and 350 microns thick (Figure 3). An elliptical frame chosen for its large and smooth actuation determines the components' base geometry. This frame is further completed by fern-like extensions to enhance the visual and motile quality of the structure. The lamination of the frame and supplementary reinforcements onto the elastomer is made possible by the adhesive properties of the elastomer itself (VHB tape 4910). A conductive coating composed of nano-carbon tubes solution is further applied onto the elastomer, before releasing the structure.

The construction of the individual elements of *Reef* confirmed that the basic principle allows for wide-ranging interpretation. The practical design principles included: (1) A flexible frame composed by as little as a single sheet of plastic material; (2) freely decorated sheets; (3) holes, where the shape dominates the response; (4) Reliable frames with holes with smooth features; (5) A frame with high activation motility - usually when the relaxed state does not appear highly compressed – a transition from a completely crumpled state to a completely flat and open state is presently not possible.

Despite the use of high-tech materials and technologies, the making of *Reef's* individual components relies on a simple manufacturing process, where the transformation of standard flat materials leads to complex 3D structures. The assembly of these structures was essentially hand-crafted, leading to a labour-intensive process, where about three hundred and fifty pieces have been laminated together to produce about fifty components. While this demonstrates the accessibility of the method, the production could easily be up-scaled through the lamination industry chain where pre-stretching and sandwiching techniques are already well-established. However, it remains a delicate process. We experienced a high rate of loss in the actuation of the modules due to the extreme fragility of the elastomer. The application of conductive coating and aluminium foil tape electrodes are crucial stages in the delivery of a fully-functional structure. Surface defects such as: micro-holes, irregular carbon deposits etc can impact on the smoothness of the actuation and create a risk of short-circuiting the structure. Further improvements need to be developed to insure reliability, notably the design of more flexible electrodes.



Designing With
Energy Flows



Figure 5. Digital simulation anticipating *Reef's* overall dynamics.

In terms of interaction, our aim was to explore how domestic spaces, instead of ignoring natural rhythms and cycles could become an integral part of the architecture and to encourage the inhabitant to reconnect with natural and biological temporality. Rarely investigated as an intrinsic medium for architectural vocabulary, wind seemed to be the most interesting element since it is a natural agent of geometric transformation in the outside world while partially, if not completely, blocked inside.

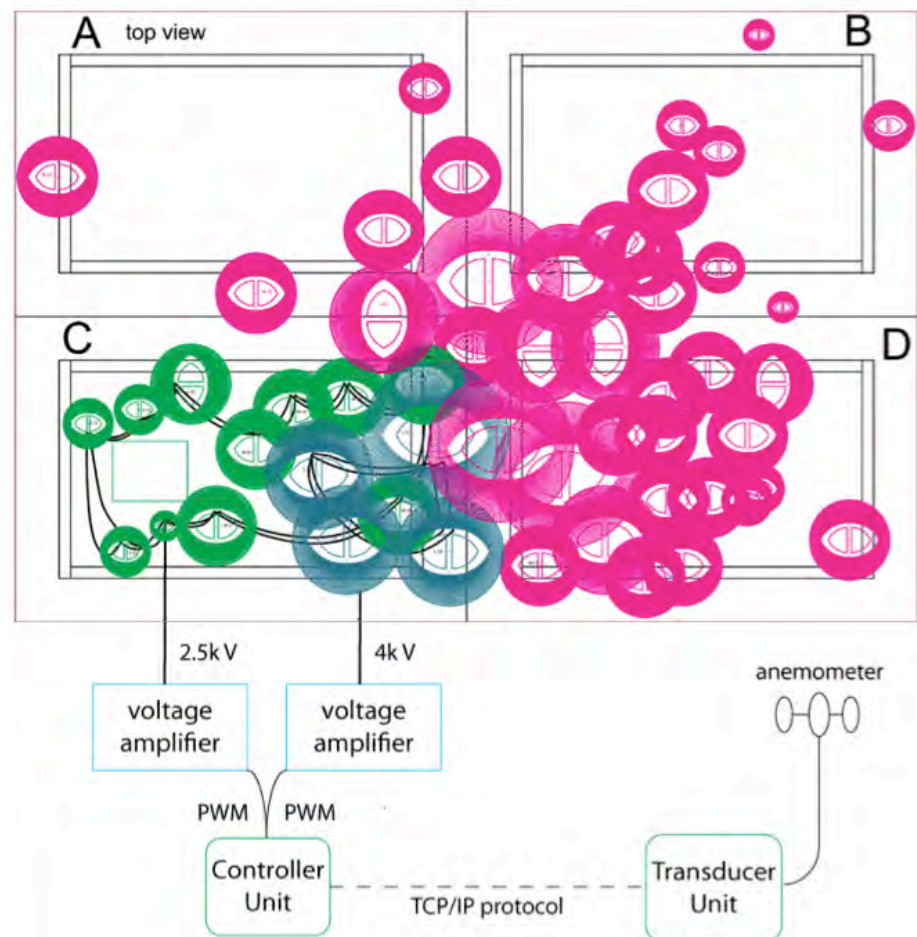


Figure 6. Top view of *Reef* and its interconnective circuit.



Initially, digital simulations were used as a drawing tool to anticipate the overall dynamic of the installation as a responsive environment (Holden Deleuran, Tamke et al, 2011). By integrating material properties directly into digital models via Maya® 3D animation software, complex interpretations of the wind's dynamics through the responsive minimum energy structures could be anticipated. The translation of wind intensity by their pulse, their degree of aperture and the directional propagation of these movements to tell wind's direction were considered. Actuating different size of modules to refer to various wind speed was also taken into consideration. However, if digital simulations were particularly useful to visualise the overall dynamic of the installation, the development of a graphic language was made necessary to communicate and discuss these various temporal logics. Several attempts were made, leading to the design of musical stave-inspired language, where the vertical position of the note indicates the degree of aperture of the minimum energy structures, while its value indicates the wind velocity to which the structures respond.

Mappings between wind speed and the geometric behaviour of the modules have been devised based on a shared frequency metric. Using an anemometer, we calculate wind speed as a sequence of micro electric pulses from which we derive a base frequency. More precisely, pulses generated by the anemometer are converted into analogue voltage using a low-pass filter and then quantised by an analogue to digital converter unit (ADC) producing a digital value. Such readings are continuously transmitted over the internet to a control unit responsible for mapping sampled frequencies to fit the desired dilatory behaviour of the modules. This is achieved by transforming the wind speed frequency into related pulsatory control patterns, activating the membrane and thus transforming the shape of Reef's modules.

Depending on the shape and size of the modules, between 2k volts and 4k volts need to be generated by the control unit and applied to each module in a parallel circuit. A special voltage oscillator amplifying control voltages from 0-5 volts to 0-8k volts is used to drive the modules. Using our microcontroller pulse-width modulation unit (PWM), we are able to programmatically generate control signals and derive visual patterns by activating the elastomer's membrane.

Our experiments showed that control of our modules' morphology was optimum when using slow and incremental actuation of the membrane. Consequently, we developed control algorithms actuating the shape of the module following an organic, dilatory, and cyclic tempo giving it an interesting pulsatory behaviour and thus suggesting a symbolic relationship to nature



Figure 7. First building iteration of Reef at 1:1 research by design exhibition, DKAD, Copenhagen, 2011.

Reef Iterations

Reef was tested by building two full-scale iterations. The initial version was developed as a composition of 50 minimum energy structures for the '1:1 research by design' exhibition at the Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen (Figure 6), while the second iteration was developed within our studio (Figures 1,2,7). Distinction between the two settings relies essentially on the scale and contextualisation of the installation.



Figure 8. Reef - reconnecting nature, the home and its inhabitants through electro-active polymers.

The first iteration was developed as a 180 x 215cm ceiling surface, each comprising three sizes of components: XS, S and M. In terms of dynamics, constraints of the physical world made it necessary to simplify the level of subtlety permitted by digital speculations. The tempo of each structure's aperture was constrained by the minimal time required for the



elastomer to un-stretch. Above 30 beats per minute, the pulse becomes almost imperceptible. Therefore, the translation of wind speed by the pulses of the structures can only occur at a slow tempo. On the other hand, tests on single components have let enabled us to envisaged the translation of wind speed by the amplitude of the apertures of the structures would be more effective as they allowed a more refined control. However, although built following the same method and materials, components' amplitude of aperture would vary a lot from one component to another, making the programming of the surface completely random.

The final strategy resulted in the actuation of the surface by translating wind speed through the pulse of the structures. Results were compromised by a series of technical failures, which allowed us to actuate only 5 out of 50 the structures. However, the break-down of one high-voltage amplifier revealed the potential of the hanging structures to respond directly to indoor airflow by shivering, suggesting further possibilities of interaction.

If further technical improvements had been explored – such as the up-scaling of individual components across five sizes (XS, S, M, L, XL) or a less crunched geometry to make the structures' aperture more perceptible, the second iteration was developed as to anchor Reef into a domestic context by using an interior design approach where the minimum energy structures become an integral part of the domestic aesthetic. This was made possible by engaging the structures at an early stage in a conversation with other surfaces: wallpaper, ceiling, furniture through games of colours and patterns. Its dynamic was explored through the activation of 15 of its components, materially distinguished by their black conductive coating. By increasing its surface, Reef also gained an immersive dimension, contributing to the tangibility of the tale.

Reef As A Timescape

If architecture has been usually thought of being outside time, electro-active polymers - due their active materiality - inevitably bring the idea of architecture into movement. As buildings gain dynamics, the question of how we qualify architectural temporality becomes essential. While adaptive architecture has been actively engaged in user-oriented time-space, Reef follows on work such as Vivisection (Ramsgaard Thomsen, 2007) Hylozoic Soil (Beesley, 2010) or Reef series (Reefseries), where architecture has its own behaviours, independently from any user imperatives.

Designing a home that feels, breathes and quivers at the pace of nature, Reef, rather than seeking control over the environment to fulfil the specific needs of the inhabitant, aims to develop the inhabitant's awareness of the exterior environment. By materialising the presence of wind within the interior, Reef operates a transfer in which the inhabitant is not in control of, but exposed and subject to, the rhythms of nature. This shift expresses the need for technology to synchronise with nature as a means to reintroducing a culture in which technology is less human-centred and more environmentally interconnected. Here, technology becomes the medium through which the natural world can make its voice heard, affirming its presence in an environment from which it has long been secluded.

For instance, modern architecture - whose resonance with the contemporary built environment is not insignificant - by its emphasis on values such as transparency, has visually erased the boundary of the interior and exterior while further segregating other senses. However, such elements as light, air, smell, sounds are crucial to our sensory and psychological needs: they regulate our internal body clocks, contribute to our well-being (Hoffman, 2009, p.19-21). Why can't buildings, instead of ignoring these cycles, allow us to reconnect with natural and biological temporality? By embodying the poetics of breathing, where artificial and natural environments are synchronising their respiration, Reef suggests an intuitive relationship between nature and the inhabitant. This relationship is not immediate and certainly not acquired. It belongs more to the world of transmission than communication if we understand transmission 'a communication optimised by a body', therefore 'neither immediate nor impersonal' (Debray, 2000, p.4). In that sense, Reef embraces a timescape perspective, one that emphasises the temporal dimension of the space, time, matter interdependency by developing a 'renewed sensitivity to the natural rhythms', one that acknowledges the 'complex temporalities of contextual being, becoming and dwelling' and their potential for the design of sustainable futures (Adam 1998).



Perspective

Although electro-active polymers research goes back as early as the 90s, architects and designers have just started engaging with what they have to offer. If Reef shares similar concerns with *Spaceshift* - a project exploring electro-active polymers for materialising a more sensitive environment through the design of shape changing wall-membranes (Kretzer, 2011) - its value precisely resides in addressing such questions, not only by investigating issues of structural or aesthetical performance but fundamentally by engaging electro-active polymers in questioning how they alter, by the simple fact of their presence, our apprehension of reality, especially how they contribute to the shaping of temporal tectonics. In other words, which sense of time and which temporal habits are they distilling, which kind of relationships between nature, the home and its inhabitant are they suggesting.

Reef also shares strong links with Philip Beesley's responsive environments (Beesley, 2010), similarly attempting to provoke the inhabitant into developing awareness of the flows in which architecture and the inhabitant are immersed. Equally evoking a world in which technology and nature are merging together, the works particularly differ in their technological materialisation. If they follow a similar digital crafting process, Reef is built upon radically new types of actuators that have rarely been experimented with at such a scale and in such a context. As they operate at the molecular level, they present a more holistic approach to actuation. Dielectric elastomer actuators possess a particular dynamic language with an inner aesthetic. Reef, by unfolding the process through which three-dimensional dynamic patterns express wind features within the home, poses the basis for the development of a dynamic vocabulary exploring the inherently fluid-like and organic motion of such materials. Hence, Reef can be given the role to also express other extant features, such as water flow in a river or waves crossing a bay, justifying our view of Reef as an expressive tectonic display drawing the outlines of a transnatural culture in which technology fuses with nature.

Acknowledgments

Reef is the result of a crossdisciplinary collaboration developed with the support from the Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation via Aurélie's position as PhD in CITA, Centre for IT & Architecture, Copenhagen, in collaboration with TFRC, Textile Futures Research Centre, Central Saint Martins, University of the Arts, London. PhD supervision: Carole Collet, Mette Ramsgaard Thomsen. With the sponsorship of MetOne and Ok Design.



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