

# Thermochromic Animation

## *Thermally-informed and colour-changing surface-configurations*

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*All factors of thermal comfort are invisible to humans and do not (yet) impact visual navigation in the built environment. Thermochromic materials change their colour relative to temperature. In architecture, their applications as responsive ornaments and as intelligent composite systems are discussed. Nonetheless, design research on their use together with computational design is scarce. This study investigates thermochromics concerning architectural surfaces. Design and material experiments were conducted to test the hypothesis that thermochromic animation can be configured to visualise invisible parameters of thermal comfort. Scale prototypes were fabricated from different materials and coated with thermochromics. They varied in layer number and sub-coatings. The colour change was observed with several instruments. Heat transfer simulations of digital doppelgangers accompanied the physical experiments. The results suggest that this method can be used to configure thermochromic animation. This can be implemented into a procedural design model for porous and multi-layered thermochromic surfaces in the future. In this, digital simulation and material-based design are combined in a method that advances the use of thermochromic materials in the context of digital architectural design.*

**Keywords:** *thermochromics, fabrication, simulation, materials, colour*

### INTRODUCTION

Buildings create micro-climates and one of their key functions is to provide a certain level of thermal comfort. The following paragraphs investigate a method to design, predict, visualise, and fabricate *thermochromic response (TR)*. This can help to communicate invisible parameters of thermal comfort and create an environmentally responsive, polychromic ornament.

### **Thermal comfort**

Comfort can be defined as being satisfied with the ambient (Hens, 2016). The interior climate quality is quantified by the inhabitant's sensation of warmth. This is the result of four physical parameters: air temperature, mean radiant temperature, relative airflow, and humidity. All four can be affected by architecture. Two more factors exist that can be controlled individually: metabolic heat production and clothing (CIBSE, 2006). Special attention is given to the direc-

tion of exposure. Non-uniform exposure, e.g., turbulent draughts or heat from local radiators, increase discomfort. Defining a specific model for thermal comfort in our dynamic urban environments is challenging (Greenberg et al., 2017). Concepts of adaptive thermal comfort are increasing in popularity. In the context of climate change and sustainability, non-uniform models of thermal comfort and the role of the variability of indoor conditions are discussed (Mishra et al., 2016). Until recently, low energy prices allowed levelling a lack of environmental design by artificial air-conditioning. Consequently, the changes in the global economy and the looming climate crisis have reinvigorated the study of thermal comfort over the past two decades (Nicol & Roaf, 2017). In the case of naturally ventilated buildings, thermal adaption by occupants can help to achieve comfort without air conditioning (Etheridge, 2012). None of the factors is directly visible to humans (Hens, 2016). Therefore, they currently do not impact visual navigation in large spaces (Figure 1).

### ***Perceiving the invisible***

This research investigates a design and fabrication method combining thermochromic materials and digital simulations for architectural elements. They can communicate invisible parameters of thermal comfort to a building's inhabitants. It specifically aims to identify key parameters for design, fabrication and simulation which can constitute a foundation for future research into parametric design methods. Therefore the paper explores the relationships between temperature, topology, and thermochromic materials by designing, fabricating and testing a series of prototypes for evaluation. Cupkova et al. clarified, that surface patterns and topology can significantly modulate the thermal mass and heat transfer behaviour of cast panels (Cupkova & Azel, 2015). While the colour of a surface is visible, its temperature is not. Our skin on the other hand senses temperature but not colour. Visualising factors of thermal comfort through material configurations would change its mode of perception from pas-

sive stimulation to active perception (Gibson, 1966).

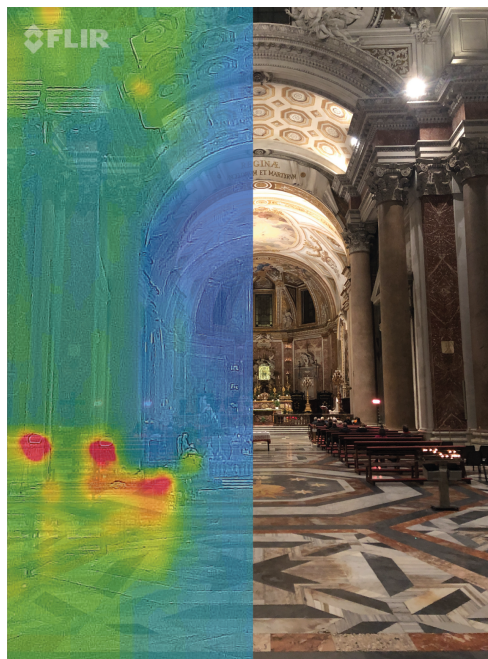


Figure 1  
The parameters affecting thermal comfort are invisible to human eyes. Therefore, inhabitants rely either on knowledge to find comfortable areas or evenly temper the entire space. Santa Maria degli Angeli e dei Martiri, Rome, February 2020.

### ***Information and ornament***

The potentials of smart- or information materials have been highlighted by others (Kretzer, 2017) (Addington & Schodek, 2005). Their use in architecture includes interior and exterior applications. Thermochromic response (TR) has been studied extensively and some applications in architecture have been suggested. Nonetheless, its position in the architectural discourse is strongly tied to that of building physics, environmental performance, and sustainability. Since many such materials lead to colour changes a closer examination of the role of colour is required. Surface colour or lighting has no significant impact on thermal comfort (CIBSE, 2006). Any psychological effect of colour in architecture is outside the scope of this paper. In architecture, colour has always played an important role. During the poly-

chromy debate in the 19th century, it has been argued whether or not ancient Greek architecture was mono- or polychromic (Semper, 1834) (Figure 2). Debates were whether whole surfaces or only selected features were coloured (Ziesemer, 2003) and if ornament ‘animates’ the dead surfaces and rigid articulations (Wölfflin, 2000). Some colours have an impact on the environmental performance of a building (Azarnejad, 2017). As ‘surface conditions’ ornament has the potential to substitute tectonics as means of spatial organisation (Picon, 2010). A difference must be made between smart materials, as materials that have an inert intelligence, and a smart application of materials, as informing the placement and configuration of materials. This paper investigates an overlap between the two. From this review the following research question can be derived: How can material intelligence be used to visualise factors of thermal comfort?

Figure 2  
Detail of the  
Parthenon,  
Acropolis, Athens.  
Painted by Gottfried  
Semper. 1836.  
Public Domain.



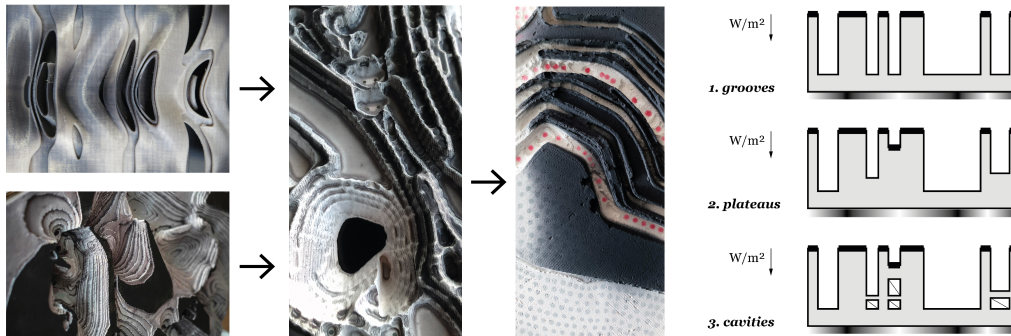
### ***Thermochromic response***

Materials that visibly change colour relative to temperature are called thermochromic materials. When applied as a coating, the underlying material is often

referred to as ‘substrate’ (Grafstein et al., 1968). Two conventional thermochromic systems are liquid crystals and leuco dyes (Kretzer, 2017). Several different thermochromic pigments with varying phase change temperatures can be mixed to achieve a more complex TR. In the context of architecture, applications of thermochromics as responsive ornaments and as intelligent composite systems have been explored (Meagher et al., 2013). Electric circuits can be embedded inside a solid material to partially heat it. Once coated with thermochromics, patterns can be made visible on its surface (Cupkova et al., 2018). In construction, thermochromics find a commercial application as a smart, dynamic glass to control heat loads through glass facades (Seeboth & Löttsch, 2013). From this review the following research question can be derived: How can TR be programmed, configured, and fabricated?

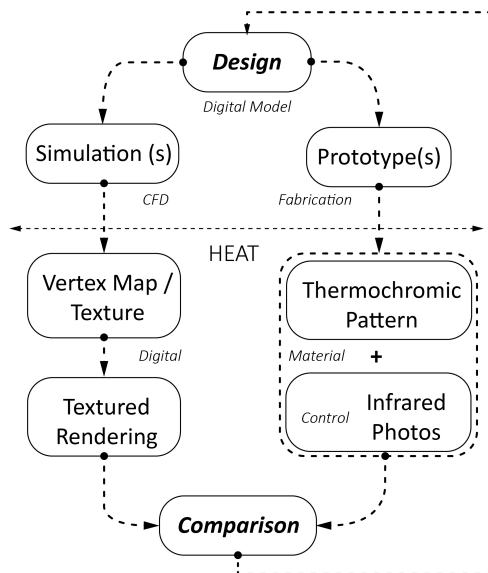
### ***Heat transfer and thermal infrared images***

‘Research on the performance of various building components has constituted a significant and long-standing domain within architectural research’ (Groat & Wang, 2013). Burry et al. investigated the integration of heat transfer performance and thermochromics for façade design (Burry et al., 2013). The role of thickness and thermal mass in relationship to geometric surface morphologies has been extensively researched by Cupkova et al. (Cupkova & Promppatum, 2017). They have investigated the heat transfer through concrete panels triggered by solar loads (Cupkova & Azel, 2015) and a fabrication process using robots to shape concrete panels (Bard et al., 2019). While previous research investigated radiation’s impact on a surface, this paper presents an investigation of the heat flux through a surface that is heated from the back. Heat transfer is the interaction of energy caused by a difference in temperature; within a medium or between media (Ghoshdastidar, 2004). Aviv et al. have investigated the use of thermal infrared (TIR) cameras to inform robotic fabrication (Aviv & Teitelbaum, 2017). Access to TIR cameras has been eased with the availability of low-cost products.



**Figure 3**  
This research combines several approaches for the base geometry. The three key strategies are grooves/ridges, plateaus/terraces, and cavities/voids.

Such cameras have numerous applications across all scales (Acorsi et al., 2020). From this review the following research question can be derived: How can designers predict and plan such TR?



**Figure 4**  
A method diagram outlining the relationships between simulation, design, fabrication, observation, and evaluation.

erature review, this paper investigates how the layering of colours, patterns, and thermochromic coatings can be configured to extend the response toolset of a single thermochromic ink by utilising the material inert mechanism of delay. The role of cavities and undercuts has been explored since most existing work deals with solid, high-density, extruded and relief samples (Figure 3). Often, the thermochromic coating acts either as an observation and measuring tool (Cupkova & Promoppatum, 2017) or as an actuated display (Cupkova et al., 2018). The hypothesis is, that through this process, the repertoire of responses can be extended towards *thermochromic animation*; beyond the binary colour change while relying on a coating that performs one phase transition.

## METHODS

Design and material experiments were conducted to test the hypothesis of thermochromic animation. Various panels were scripted and digitally fabricated from multiple materials (high-density foam, PLA, clay, plaster, cement, sand binder-jet) with varying densities. The prototypes were then coated with thermochromic pigments. The coatings themselves varied in the number of layers (thickness) and various sub-coatings (colour and pattern). The colour changes, resulting from heating and cooling, were documented using TIR cameras, video, and laser thermometers. Outcomes were analysed and compared with heat transfer simulations of digital dop-

## Thermochromic animation

Departing from previously gained knowledge on CFD-driven thermochromic articulations and the lit-



pelgangers (Figure 4). The observations then inform the next design iteration. This combination of experiment and simulation in ‘sequenced phasing’ is common in environmental design research (Groat & Wang, 2013).

### Designing with CFD

An air-flow simulation of an arbitrary wall was set up using *Autodesk CFD Ultimate 2019*. On this surface, a series of geometric features were placed. They represent abstract façade protrusions that interfere with the air flows independent of the flow direction. The results are exported as an image file. The smooth colour gradients are posterised and contoured. The resulting curves are sorted by length, displaced perpendicularly to the image plane, and meshed using VDB (Figure 5).

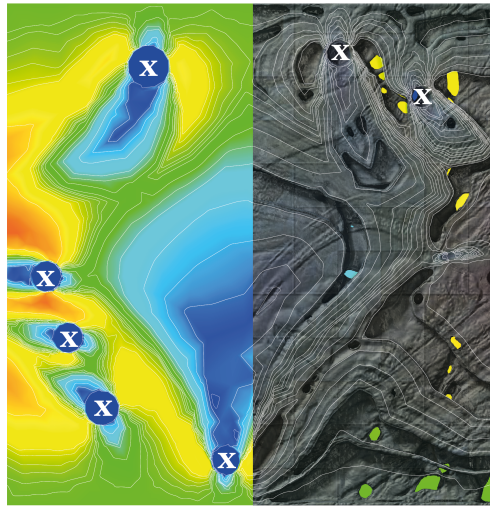


Figure 5  
The colour data of the air-flow pattern is converted into curves. They are displaced depending on their length in a direction normal to the surface plane. The results are meshed and shaded for preview.

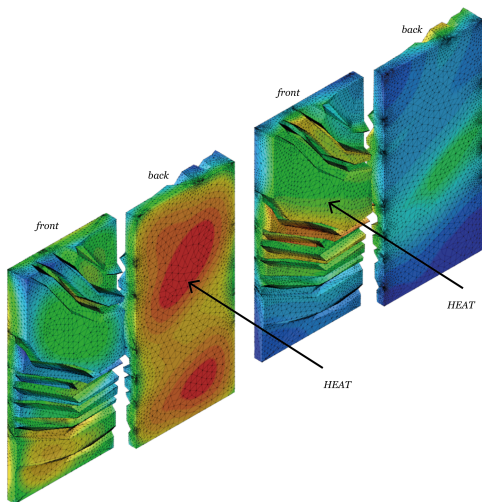
### Fabrication

This paper focuses on PLA 3d-printing and casting. Cnc-milling, clay, and binder-jet 3d-printing are not discussed. A series of 1:10 scale models (120x60mm) were printed with an FDM 3d-printer (*Anycubic i3M*) for colouration strategy tests. A deviation from the

original geometry was accepted due to time constraints. A 0.2mm layer height was used. Consequently, the resulting panels had a lower resolution than the original polygon mesh. The prints were used to make reusable silicone moulds. Plaster, concrete, and white cement were used for casting. Some of the substrates were mixed with yellow thermochromic pigment powder at different ratios (8g, 4g, 2g per model) to investigate an alternative response strategy to coating. Pouring material with different densities into the surface depressions has been explored as well, but is not part of the results shown here because of the experiments pre-mature state. The resulting panels were 3d-scanned with photogrammetry using *Epic's Reality Capture*. The deviation between the original meshes and the scanned ones was analysed by overlaying the meshes in *Rhino6*. Across each panel, it ranged between 1-2mm. Since the resulting meshes had to be reduced heavily for the simulations, this deviation was accepted.

### Heat transfer simulation

The photogrammetry meshes were reduced from an average of 80k to around 300 faces using the ‘\_ReduceMesh’ command in *Rhino6*. The scope of the simulations was to understand which parts heat up quicker than others. The focus was on the graphic output to determine different zones and to identify patterns. Therefore, a simple setup was chosen with a heat flux boundary condition of 200 W/m<sup>2</sup> applied to the back. For all other surfaces, a film coefficient boundary condition of 20 W/m<sup>2</sup>C was applied for convection with a 10°C reference temperature. The simulation type was set as a transient with 20 timesteps. For initial simulations, during the design process, *ANSYS Discovery Live 2020* was used to get quick visual feedback. Since the academic licence of *ANSYS* has only limited export functionality, *Autodesk CFD 2019* was used in some cases (Figure 6). It allows exporting results as FBX files with an add-in (*Showcase Exporter 3*). The files include the simulation results as vertex colours.



to identify patterns. Therefore, a sufficient differentiation of data across an image was satisfying and parameters like the accuracy of temperature readings were ignored. The orthogonal top views of the specimens were compared to the digital simulations using computer graphics; both single images and sequences. The evaluation criteria for the TR were **contrast**, **diversity**, and **speed**.

Figure 6  
Digital heat-transfer simulations allow us to predict and design the heat-map patterns on the opposite side of the relief.

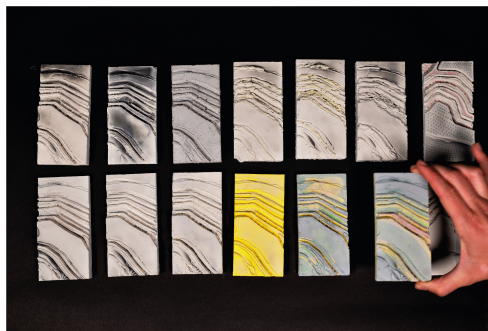


Figure 7  
A series of 'hot' panels just before cooling down. The different substrate patterns and colours are visible.

## Coatings

The black thermochromic ink has a phase transition temperature of 27°C. This is close to the temperature, which, together with high levels of humidity, generally cause discomfort (CIBSE, 2006). This research used liquid crystal thermochromics. It consisted of two components; a 1:1 mix of thermochromic slurry and sprayable lacquer. The substrate coatings beneath were either applied with marker pens, thermochromic powder (28°C), or acrylic spray paint.

## Experiments and comparison

For observation, the scale parts are placed 40-50mm over an infrared heating plate (150W). Each series of panels was exposed for ten minutes. The colour change was documented using a mounted DSLR camera, a handheld laser thermometer, a handheld smartphone TIR camera (*FLIR One iOS Gen 3*), and a USB TIR camera (*FLIR Lepton 3 + GroupGets Purethermal-2*) mounted 150mm below the DSLR (Figure 8). The focus of the observations lied on the relationship between geometry and TR. The thermographic data was used for control and reference and

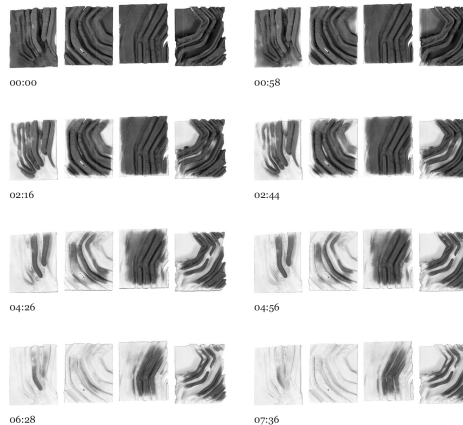


Figure 8  
Experiment setup.

## RESULTS

The substrate-inert colour has a big influence on the fabrication process. Neutral, pale material colours - such as plaster, cement and white PLA - perform better than more saturated ones. The latter requires extensive priming which adds steps to the process. The experiments show that an even thermochromic coating is crucial. If the coating layer is too thick, the colour does not sufficiently shine through. (Figure 7) Patterned substrate coatings tend to work better than solid ones because they use the natural contrast between substrate material and pattern. They reduce the required thickness of the thermochromic coating. Tool traces of the printing nozzle yielded a higher surface complexity leading to intricate features. This yielded a more effective TR compared to smooth areas. The TR was stronger, and more visible, wherever small elements prevailed. The same applies to imperfections from the casting process such as enclosed solids (gravel) or voids (bubbles). The effect is generally stronger the thinner intricate a plate's topology is (Figure 9). Designs with relatively deep protrusions/depressions tend to be more successful than flat but patterned ones; *depth* outperforms *thickness*.

Figure 9  
Snapshots of a ten-minute long exposure to IR radiation from below.



## DISCUSSION

The results suggest that the relationships between material thickness, topology, and TR can be used to configure thermochromic animation. Thermochromic pigments change colour at a specific temperature. When directly exposed to heat, e.g. from solar radiation, the colour change occurs once the surface temperature exceeds this material-specific value. When the backside of the surface is heated, the colour change is triggered once the substrate material's temperature exceeds it. Digital simulations are ubiquitous tools common in architectural and environmental design (Groat & Wang, 2013). Besides material experiments, they are key for thermochromic animation. The results show that the hypothesised method to configure and program TR is feasible. Thermochromic surfaces can be programmed by informing the composition of the substrate layers with heat transfer simulations. The simulations can successfully predict the response and the method can be used to highlight surface features. Prototypes can be fabricated in various ways. Creating moulds for casting appears to be a sustainable solution since digital fabrication per part is reduced. Response variety can be increased by using different casting materials, inlays, and pigments. A comparison of the outcomes suggests that the direct correlation between geometry thickness and TR can be directly used for design without extensive simulations. Some software solutions allow exporting simulation results as coloured meshes or CSV tables. This data can be imported into CAAD platforms using the FBX file format or via node import for design purposes. In general, the following can be said about thermochromic animation and its configuration:

- Intricate surface articulation leads to a stronger TR. Imperfections, tool traces, paint-pooling, coating evenness, and thickness show potential as design strategies; *diversity, contrast*.
- Thin and porous geometries perform better since their thermal mass is comparatively low. They also have a higher surface area; *speed, contrast*.

- Cavities and inclusions have an impact on the TR. The trapped air insulates and impacts the heat transfer path inside the geometry; *speed, contrast, diversity*.
- Flat surfaces (backsides) and reliefs perform worse than geometries that are equally intricate on both sides; *speed, contrast*.

### Critical reflections

Some of the panels heat up unevenly. TIR images show that the heating bed is not warming up consistently. As a result, panels close to the border remain cooler than the ones in the centre. The location of a panel concerning its neighbours has an observable effect on the evenness of the colour change too. Panels in the centre of an arrangement warm up quicker than those on the perimeter. The sides of each panel should be insulated for evenness in future experiments, as suggested by others (Cupkova & Proppatum, 2017).

### Limitations

Strategic placement of layers reduces UV degradation of the thermochromics by shielding certain parts of the geometry from light (Figure 10). The software interface between thermal simulation and generative design is not sufficiently developed yet. The thermal simulation results can be exported as meshes containing vertex colours or as node data. A workaround is to export the uncoloured mesh data and then texture map orthographic images onto the mesh using computer graphics. The *Lepton 3* TIR

sensor does not provide radiometric data. Technically, temperature data can be read from the resulting TIFF files and converted into RGB values using *ImageJ*. This requires manually calibrating the camera using temperature references. Future experiments must be done using a *Lepton 3.5* which provides radiometric data at a comparable price. The image size of 160x120px is too low. Artificial intelligence can be used to enhance the output. 3d-printing offers great design freedom. To up-scale the process, robotic clay or concrete 3d-printing appear feasible. Their downside is reduced design freedom due to fabrication constraints (continuous paths). Binder-jet 3d-printing could be a possible alternative, although the results tend to be extremely porous with high absorption rates.

### Future studies

The implementation of cavity spaces must be explored further. In the next steps, the outcomes can be implemented into a parametric model for the generation of thermochromic surfaces according to environmental data. Developing a method to implement the thermal analysis back into a parametric model is key. On this basis, digital simulation and material-based design are combined in a technique that advances the use of thermochromic materials in the context of architectural design (Figure 11). The outcomes suggest investigating how such a response can be combined with augmented reality. Complex environmentally responsive trackers could be designed to act as input devices for AR applica-

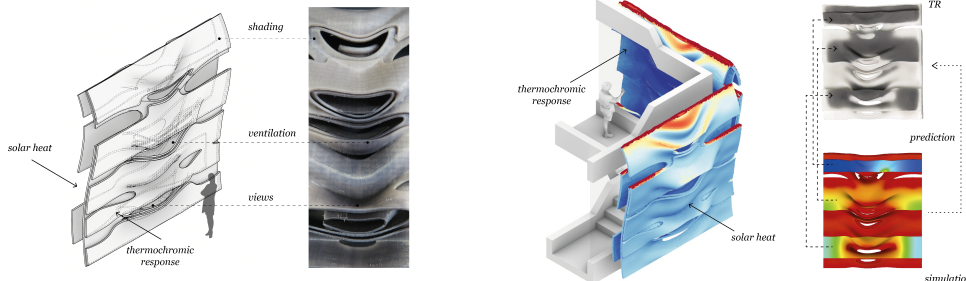
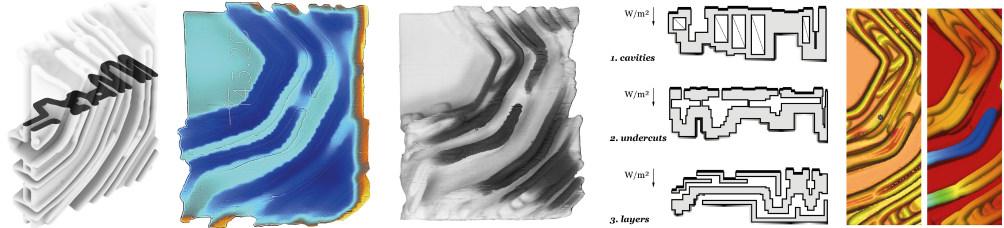


Figure 10  
A multi-layered curtain wall element would allow merging environmental performances such as shading and insulation with an integrated TR.

Figure 11  
From left to right:  
3d-model,  
thermographic  
image (TIR),  
thermochromic  
response (TR),  
schematic sections,  
thickness, digital  
simulation. Three  
key strategies are  
suggested: cavities,  
undercuts, layers.



tions on smartphones or glasses. Future, and ongoing, research will focus on larger scales and 1:1 application. In the context of the climate crisis environmentally friendly and non-toxic solutions must be investigated. Studies on non-toxic thermochromic pigments exist (Seeböth et al., 2013). Cnc-milling of wooden formwork and clay 3d-printing should be investigated.

## CONCLUSION

A combination of digital simulations and material experiments can be used to configure the thermochromic response of architectural surfaces. Layers, cavities, overhangs, and coating affect the response. Reliefs offer limited possibilities due to the high thermal mass of the base surface. The experiments investigated the topic on both a material and an architectural scale. By thermochromic material programming, surface articulations can visually highlight formerly invisible parameters of thermal comfort over distance. The environmental condition at the surface datum is therefore extended into space. The observable increase in complex geometries in architecture together with higher demands for environmental performance will require advanced methods to simulate and design. Thermochromic animation allows programming the behaviour of responsive surfaces in architecture. In doing so it contributes to the fields of thermodynamic architecture and digital ornament. A closer interlinkage between material, geometry, colour, and texture will extend the architectural vocabulary to better communicate between the natural and the built environment.

## ACKNOWLEDGEMENTS

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