Thermochromic Articulations

CFD-Driven Surface Topologies

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ABSTRACT
The ongoing research presented in this paper lies on the threshold between computational design and digital fabrication with a strong focus on emergent techniques for environmental design. The main hypothesis is, that with an increasing granularity of thermal comfort - observing a trend towards more heterogeneous indoor microclimates – new design challenges arise.

Architectural fabrics will be required to communicate indoor climate conditions to the inhabitants, to maintain high levels of thermal comfort locally but specifically. This research investigates a novel generative design methodology, which links computational fluid dynamics simulations, robotic fabrication and material-inert performances. The resulting environmentally active panels respond to climatic conditions and by this communicate parameters of thermal comfort, such as temperature, airflow, and humidity, to the inhabitants.

This paper presents a digital design workflow, a prototype for a thermochromic panel, and speculates on potential development. Communicating invisible parameters of thermal comfort to users is a crucial requirement when designing large continuous indoor volumes, when blurring the dichotomous duality of inside and outside and when designing highly porous architecture.
INTRODUCTION
To negotiate between inside and outside, to communicate between architectural fabric and human perception, designers use a variety of tools. Advances in computational design and digital fabrication have enabled architects to create highly complex, idiosyncratic and high-performance buildings. Most architecture today, nonetheless, requires equally complex mechanical and electrical systems to maintain required levels of thermal comfort. (Kreysler 2010) In this light, the research presented here aims to contribute to the fields of digital generative design, computational environmental simulations. By this, the outcomes suggest a digital design methodology and a digital fabrication method, including smart materials, which can help to elevate the use of air in architecture from a purely metaphorical to a phenomenological – materializing its effects on the architectural fabric. (Abalos 2015)

Context
Still, we cannot communicate what is invisible. The consequence of this is total climatic homogeneity. This research explores an alternative approach, propagating an architecture wherein indoor climate is heterogeneous, passive and adaptive. Consequently, new design strategies need to emerge, which communicate the aforementioned invisible parameters of thermal comfort: temperature, air movement, humidity. Contrary to the often-proposed method of locally controlling indoor climate, this research discusses a passive approach of visualization, through materiality, as well as a deeper implementation of computational fluid dynamics (CFD) into the generative design process of both volumes and surfaces in architecture. (Addington 2009)

Using tools - created for optimization purposes in building physics (Figure 1) - as a generative and intuitive design interface, to create environmentally performative architectural elements, can help to overcome the often-criticized disassociation between digital architecture and human inhabitation.

Background
With ever more complex interior spaces - and an increase in the availability of shapes and forms to design with - in architecture, new methods to communicate indoor climates are required. To visualize the invisible factors of thermal comfort to inhabitants becomes crucial when designing continuous curvilinear spaces. Research on the use of thermochromic ink, as a responsive tool in architecture, has been published recently by a series of researchers. Existing work investigates the use of thermochromic ink as a new form of dynamic ornament, as embedded responsiveness to communicate the thermal performance of solid constructions and as conveyors of information in the environment.
built environment. (Cupkova, Byrne, and Cascauval 2018; Meagher, van der Maas, and Aebeg, Christian and Huang, Jeffrey 2009; van der Maas et al. 2009) Understanding surface articulation as an interface between architecture and the user, and the depiction of natural phenomena in the built environment are core aspects of ornamentation. While those can be figural or abstract, those articulations always communicate between object and subject, nature and human or architecture and inhabitant. (Bloomer 2000)

The use of CFD to generate surface articulation is novel. By simulating the natural forces and the prediction of their effects on clean surfaces, allows the designer to compute a novel relationship between architecture, nature, and ‘subnature’. (Gissen 2009) The articulation of inert performances of certain geometries, in regard to their interaction with environmental forces, leads to a novel canon of surface aesthetics and generates new forms of quasi-parametric patterns. (Schumacher 2017) The use of simulation software to generate form and articulation is referring to a new form or ‘anthropogenic nature’ which suggests that with a deeper understanding of nature’s principles and the use of computational tools, architects and designers can emulate, simulate and create a built environment, which is unrelated to the romantic image of ‘undisturbed nature’. (Vrachliotis 2008)

**METHODS**

CFD software is readily available and increasingly accessible for architectural designers. For the work presented in this paper, Autodesk CFD 2019 and RhinoCFD have been used to create the initial airflow studies. The output was then used as a basis for a generative design process, using image maps to create digital terrains. In further steps, the digital model was CNC-milled out of XPS and coated with thermochromic ink (Figure 2).

**CFD Simulations**

The CFD simulations for this design study were a steady state simulation of air blowing over a flat surface with 3 m/s. On that surface, a series of idiosyncratic objects were placed to function as obstacles for the airflow. The objects acted as proxies for site-related or programmatic constraints in future applications of the design methodology and are scale less. The turbulence created by those obstructions is the main driver for an emerging pattern of high intricacy (Figure 3).

**Geometry Generation**

The resulting graphics - static bitmaps and transient animations - have been consequentially used as data input into 3d-modeling software such as Rhino 6 and Cinema 4d R20 (CAD). After a comparison of the results, CAD was chosen for the next iterations due to better meshing for fabrication (Figure 4).

**CNC Fabrication**

The CNC fabrication was done at a workshop, using a standard three-axis machine. Regular light blue insulation foam was used as a material for the 1200x600x100 millimeters block (Figure 5). A 6mm bit was chosen as a compromise between speed and resolution. A high level of resolution

4 A series of digital 3d models resulting from a variety of different CFD simulations

5 XPS foam after three axis CNC milling in the workshop

6 This is ACADIA-Figure Caption. Delete text box if not necessary. Igni dolent a dolore, officio blameni enimi, sequi blaccus non places sit.

7 Left: Emerging green color below the thermochromic ink layer above a temperature of 27°C; Right: Thermal image showing the temperature distribution in relation to geometry
was desired, achieve greater differentiation between voluminous and porous areas. This was an aim because the project foresaw to visually analyze the relationship between color change and geometry when exposed to heat.

**Thermochromic Coating**
Thermochromic ink has the ability to change color when exposed to heat, or turn transparent. (Meagher, van der Maas, and Abegg, Christian and Huang, Jeffrey 2009) The ink used in this prototype (Figure 6) changes its opacity above 27°C – the temperature threshold above which rooms are widely perceived as uncomfortable - from black to transparent. By this, the surface reveals the underlying color coding which has been previously applied. (CIBSE 2006)

**Visual Analysis**
The resulting prototype has been exposed to heat from both radiation (infrared) and hot air flows (hairdryer) in a series of experiments. The results of normal RGB images and thermal imagery (Figure 7) have been compared. Before coating the panel, the primed XPS has been spray painted with a color gradient from yellow to blue in relationship to the z-depth of the panel (Figure 8). During the experiments, it became clear that the applied layer of thermochromic ink has been too thick. Consequently, a shift from black to white instead of transparent occurred when the panel was exposed to temperatures above the threshold of 27°C.

**RESULTS**
The results of the experiments are promising and allow for speculations on future applications of this method. The hypothesis of climatic granularity - as a driver for new digital design methodologies - is discussed in the following paragraphs. The principal results are promising but require further refinement regarding the automation of the CFD simulations and digital fabrication, as well as the relationship between the static environmental ornament and space itself. Since this short paper is about in-progress work, the following chapters aim to give an overview of ongoing and planned research by the author in this field.

**Computational Design**
The prototype’s geometry presented in the past chapters was created by a linear extrusion. Next steps will introduce a dynamic generative process, that allows for digital feedback loops. This requires the simulation’s node data to be directly fed into the software that generates the geometry (via .csv). An appropriate workflow is currently under development. To reflect environmental conditions more precisely, a higher level of intricacy is desired for the surface articulation (Figure 9 and Figure 11).

**Robotic Fabrication**
Currently, the use of robotic arms instead of a CNC-mill analog by the author (Figure 10). This would allow for greater formal freedom and potentially allow for a more collaborative fabrication process, involving more than one machine and potentially parallel human interaction. The robots allow to automate this process and potentially introduce machine-human-environment interaction. By this, the research will investigate the relationships between analog
materials and digital fabrication as well as new aesthetics emerging from environmentally driven articulations.

Critical Reflections
As mentioned in the previous chapter the thickness and composition of the thermochromic layer require refinement to achieve transparency. This will be possible with a new spray system. The costs of the ink are comparatively high, which makes the entire process expensive and hard to scale up. A more sophisticated method, involving parametric patterns, as suggested in 3.2 seems promising to reduce expenses and increase feasibility. The current method cannot create undercuts and therefore results in topologies with limited complexity. Here again, a move to robotic milling instead of a CNC router must be investigated. The application of a geometry dependent color coding (Figure 8) was a first step towards embedding more information into the panel, which is then released accordingly when exposed to the environmental conditions. By increasing the resolution of the fabricated articulations, the visualization of climatic granularity can be improved and therefore the information, given by the surface about the space, enriched. This would open up design possibilities that create different readings according to the distance between object and beholder; communicating both local factors of thermal comfort and global navigation through indoor and outdoor spaces.

CONCLUSION
The prototype demonstrates the feasibility of the technique described here. Accessible literature establishes a theoretical framework. Within this, the relationship between inhabitant and architecture is evaluated in regards to human-surface-environment interactions. Consequently, the CNC-fabricated prototype successfully acts as a case study for a digital design methodology. This design methodology combines a novel generative approach, utilizing CFD as a tool to generate intricate surface articulations in response to space, with the use of thermochromic ink as a visible indicator of thermal comfort. The latter has been strongly inspired by the references mentioned. In regards to the thermochromic aspect, the project contributes to the field by using it as an additional layer rather than the information carrier itself. The combination of geometry-inert response to heat exposure, based on a varying and intricate surface topology, and thermochromic pigments has the potential for architectural applications; both indoor and outdoor. Indoor this can help inhabitants to read microclimates and navigate through spaces with heterogeneous thermal comfort zones. The use on the outside of the architectural envelope suggests a potential communication of ‘intensive properties’ to urban space. (Reiser and Umemoto 2006) Therefore, this research can contribute to the wider discussions on sustainability, ecology in the built environment, digital design and robotic fabrication. The use of digital generative design linked with CFD and robotic fabrication will be a core part of the author’s future research into an understanding of architecture as ‘a three-dimensional relationship, physical and sensual’ that is actively enabled, passively communicating and approachable. (Reisner 2018)

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REFERENCES


IMAGE CREDITS

All drawings and images by the author:

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