Chromogenic Composites

A case study for combining thermochromics with heat transfer simulations and digital fabrication in architectural education

Andreas Körner
Universität Innsbruck, Institut für Experimentelle Architektur - Hochbau
andreas.koerner@uibk.ac.at

Over the last few decades, environmental considerations have become increasingly important in architecture. To predict and simulate material changes and environmental forces can help architects to articulate surfaces. In architectural education, an increasing amount of the curricula are engaging with aspects of energy design, sustainability, and environmental simulations. The successful integration of related novel technologies in education has been demonstrated in the past. This paper documents a technical seminar that focused on the combination of digital environmental simulations and smart materials to create chromogenic prototypes for environmentally responsive architectural composites. Thermochromic chromogenics are substances that reversibly change colour depending on temperature. Specifically, the task was to come up with novel techniques to combine such materials with varying substrates to achieve dynamic panels. The course design was informed by a variety of design research and learning concepts. Students were asked to use digital heat transfer simulations to predict the smart material changes of computationally designed panels. Each of the eight idiosyncratic prototypes was modified with a variety of techniques and coated with thermochromic ink to achieve complex heat signature patterns. The resulting chromogenic composites were documented and analyzed using photos and infrared thermography. The seminar's results showed that the three aspects (simulation, material, fabrication) can help to introduce eco-relevant technologies to design education. For this paper, both the outcomes and the course design itself were reviewed to better understand the co-creation process of the three aspects. This evaluation provided a rich repertoire of possibilities to combine different technologies for creative environmental design in architecture; all while maintaining an engaging teaching environment.

Keywords: *Education, Smart Materials, Simulation, Prototyping, Heat Transfer.*

INTRODUCTION

Environmental considerations are becoming increasingly important in architecture (Roberts & Marsh, 2001). This is not limited to the design of structures but includes all other aspects of building design. Digitally simulating material changes and environmental forces can help architects to articulate architectural surfaces. Educators are not only tasked with teaching essential skills that prepare students for today's mode of practice. They also must ensure that the future generation of architects is readily prepared with both technical skills and intellectual capacities to engage with future challenges. One of those, not so future, challenges is the prospect of harsher and more volatile climatic conditions which architecture must mediate. Furthermore, the idea of the "designer as an author, a sole creator, is being replaced with semi-autonomous, algorithmically driven design workflows deeply embedded in a collective digital communication infrastructure" (Marble, 2012, p. 8).

In the context of *Co-creating the Future,* this suggests developing design methods in which environmental factors have a direct agency in the design process. The author understands this theme as an opportunity to explore pedagogical aspects of teaching technical skills for environmental design, digital fabrication and simulation, and iterative evaluation through prototyping. The paper presents the course design and outcomes of a single semester's technical postgraduate seminar.

The resulting collection of environmentally responsive prototypes (Figure 1) provided a rich repertoire of possibilities to combine different technologies for creative environmental design in architecture maintaining an engaging teaching environment.

Environment, Material, Design

The research brief shared with the students at the technical seminar was designed to bring together environmental concerns and smart materials through design. The environmental concerns include invisible meteorological parameters. Smart materials – thermochromics – act as a mediator between design and environment. From an experience perspective, this is influenced by the early educational work of Lázló Moholy-Nagy. (Moholy-Nagy, 1968). He linked prototyping and experimentation to educate students about the haptic qualities of different materials through their own experiences. Frederick Kiesler's work on the other hand has been influential since it pioneered a didactic combination of biological case studies and design experiments (Phillips, 2017). Looking back over the last one hundred years highlights the continuous demand for architectural education to foster an understanding of our intertwined and interconnected dynamic world.

The combination of environmental simulation, digital fabrication, and smart materials in such a seminar promises to be a valuable learning and teaching environment that could help students to employ state-of-the-art digital technologies to improve the environment and hence, respond to the most challenging problems in our current times.

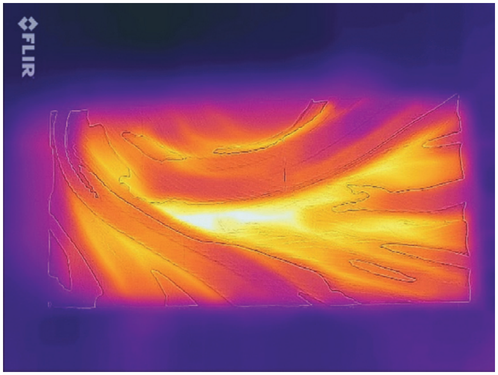

Figure 1
Thermographic image of one of the student projects. The group focused on the use of strategically placed cavities to control thermal mass behavior. Peter Kammerlander & Martin Danler

Design research

In the late 1990s, Nigel Cross formulated a set of criteria concerning *design research*. He argues, that "a major area of design research is methodology: the study of the processes of design, and the development and application of techniques which aid the designer" (Cross, 1999, p. 6). He further emphasizes the importance of *materials* and *finishes* next to digital innovations.

The course design relied on five characteristics defined by Cross (1999, p. 9):

- "*Purposive*, based on identification of an issue or problem worthy and capable of investigation.
- *Inquisitive*, seeking to acquire new knowledge.
- *Informed*, conducted from an awareness of previous, related research.
- *Methodical*, planned and carried out in a disciplined manner.

- *Communicative*, generating and reporting results which are testable and accessible by others".

Design pedagogy

In architectural education, an increasing amount of the curricula are engaging with aspects of energy design, sustainability, and environmental simulations. The successful integration of related novel technologies in education has been demonstrated in the past. Cross states that when defining design research, one encounters the "paradoxical task of creating and interdisciplinary discipline" (Cross, 1999, p. 8).

Teaching digital methods in conjunction with physical experiments and making can enhance the learning experience (Rousseau, 2021). In 1984 David Kolb developed the concept of learning cycles (Haak, 2021). The cycle consists of four steps: *Concrete experience* (feel), *Reflective observation* (watch), *Abstract conceptualization* (think), and *Active experimentation* (do).

For the seminar presented in this paper, the above-mentioned principles have been translated into a three-step framework consisting of analysis, synthesis, and evaluation (Figure 2).

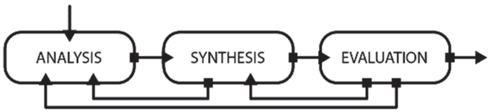

Figure 2
The Systematics Design Model consists of three iterative steps. (Groat & Wang, 2013)

This facilitates freedom for iterative design, which results in a broad range of ideas during synthesis. Several alternatives are then compared during the evaluation period to pick the ones best fitting to the task as well as most feasible to accomplish given the constraints.

Comparable courses

Design and engineering courses often face the challenge of developing engaging teaching methods that allow students to creatively approach environmental design challenges.

A series of published examples have been identified to inform the course design and to identify learning goals. Mostly they tackle one or the other aspects of the method. In some cases, for example, thermochromic materials are used only for evaluation purposes; to visualize invisible climatic factors (Burry *et al.*, 2013; Cupkova & Promoppatum, 2017). In other cases, thermochromic materials are themselves the core topic (Cupkova *et al.*, 2018; Perez *et al.*, 2018). Digital simulations are often used for form-finding purposes or design evaluation (Lally, 2009; Chronis *et al.*, 2017). Prototyping and *making* are key aspects of almost all examples, regardless of their material or digital nature (Burry *et al.*, 2013; Kretzer, 2017). In the context of this paper, the selected examples can be categorized as follows: **A)** Thermochromics as a theme to visualize heat-related phenomena. **B)** Digital environmental simulations for form-finding. **C)** Heat transfer simulations to program thermal mass.

All examples listed above publish student-work-related research, that has been produced during courses and seminars. This paper presents the syllabus and the results of a technical seminar. The course design is based on a critical evaluation of the above-mentioned examples.

Chromogenic Composites

The course relies on combining digital environmental simulations (Peters & Peters, 2017) and smart materials (Addington & Schodek, 2005) to create chromogenic topologies for environmentally responsive architectural composites. Specifically, the task was to come up with novel techniques to combine thermochromics with varying substrate materials to achieve dynamic panels. This interdisciplinary approach allowed students to create new meanings from old ideas (Vaidya, 2020).

Chromogenics can be vaguely defined as substances that give colour. This change is reversible and allows for at least two states of appearance triggered by a variety of environmental or electronic stimuli (Lampert, 2004). *Composites* imply thin material compositions that are woven, glued, laminated, or otherwise adhered together (Lynn, 2010).

Figure 3
Evaluating the thermochromic response using a handheld infrared camera. The distinctive heat signature of each panel is informed by the design process and heat transfer simulations. Catalina Tripolt & Viktor Moosmann

Aim

The aim of this paper is twofold. First, the paper aims to present the results of a technical seminar which are a series of prototypes developed by students using computational design, digital fabrication, digital heat transfer simulations and thermochromic materials. Second, the paper aims to situate the seminar within the contexts of higher education, co-creation in design and the transfer of knowledge from research to teaching.

Therefore, the following paragraphs elaborate on each of the topics, introducing relevant aspects of the work. This includes the design of the course, modes of student engagement, technical aspects of thermochromics, simulations, and fabrication. Finally, the evaluation criteria (both concerning the prototypes and the course performance), testing and learning are presented.

METHODS

The course *Chromogenic Composites* was structured in eight parts:

1. Independent literature research of relevant publications about smart materials, environmental simulations, digital fabrication, composites and dynamic ornament.
2. Class tutorials on computational fluid dynamics (CFD) and heat transfer simulations.
3. Independent development of group-specific research foci, themes, and designs (Figure 4).
4. Supervised CNC milling of topographic panels from medium-density fiberboard.
5. Independently modify the milled panels using specific techniques following each group's research foci.
6. Assisted coating of the panels using thermochromic ink.
7. Independent prototype analysis and evaluation using thermal cameras, timelapse videos and photos (Figure 3).
8. Documentation of the results and visual presentation highlighting key findings.

Figure 4
Initial scale tests (3d-print) for intentional perforation to increase heat flow through a thermochromic panel. Luis Navarro, Amy Ehringer & Kurt Brennecke

Course design and tasks

Architectural research, practice, and education contain a comparatively wide variety of methods and a diversity of subjects (Groat & Wang, 2013). The seminar was set up in a way that students used digital heat transfer simulations to predict the smart material changes of computationally designed panels. The basic workflow for heat-responsive relief panels was based on the author's previous research (Körner, 2019, 2021).

For the seminar, the workflow had to be adapted and modified to a) fit the time constraints of a

Figure 5
Comparison during testing. Hot panel (right) and cold panel (left). Above 27C the thermochromics change from black to white and then transparent. Aida Issakhankyzy & Johannes Resch

seminar, and b) establish a clear structure of tasks. First, the cohort had to form groups of two to three students. They then had to choose from a set of ten selected items of literature relevant to the syllabus. The literature was read and summarized by the students and presented to their colleagues during two sessions. Simultaneously, two workshops were provided by the author. One on CFD simulations and one on heat transfer simulations. Equipped with the necessary knowledge about the theme, each group then received the task of identifying a field of specialization. This was followed by a month of independent group work with occasional design tutorials. The design proposals, including simulations, renderings predicting the thermochromic color changes, and scale prototypes, were presented to the peers. Incorporating feedback, each group submitted a mesh file containing a topography. The geometries were CNC-milled in the workshop. The resulting panels were then handed back to each group for further fabrication steps. After this, the panels were primed by the workshop in white color. The students then had roughly a month to apply sub-coatings or other modifications before they were again sent to the workshop to be coated with thermochromic ink (Figure 5). After this final collective step, each group had the task of finishing their prototypes and testing them using an infrared-heating bed, hairdryers or other heat sources. The chromatic changes had to be documented and the results compiled in a PDF for submission.

The resulting prototypes were then displayed at the department and a final meeting allowed for feedback. Initially, the seminar was conceptualized to be held in person. Due to changes in COVID-19 restrictions teaching had to move to distance learning halfway through the course (Figure 10). Because of this, the original idea of segmenting the course into cohort-group-cohort phases was limited.

Design freedom and student engagement

The seminar participants, seventeen Master's students, were given the freedom in choosing their approach to completing the given tasks. A limited set of tools and processes were prescribed. The criteria were reduced to a minimum to allow for design freedom. Each group's approach was highly individual. This allowed the students to define their foci and agendas. The motivation was to achieve less biased, intuitive results and to increase student engagement. The initial task of presenting a chosen item from a reading enabled students to learn from each other before learning from their tutor. The fact that the workshop was organizing the CNC-milling further emphasized a flat hierarchy where multiple agents come together. Limiting tutor-oversight further forced the groups to collaborate concerning access to tools, the submission of files, problem-solving in software, and transfer of knowledge for fabrication.

Heat transfer simulations

Research that is concerned with the performance of building components is an integral part of architectural research. This is often achieved through the "combination of experiment and simulation in sequenced phasing" (Groat & Wang, 2013, p. 349). Digital heat transfer simulations help to understand the temperature differences within a medium (Ghoshdastidar, 2004) (Figures 6 & 7). Autodesk CFD Ultimate 2021 was used for the simulations (Autodesk, 2021).

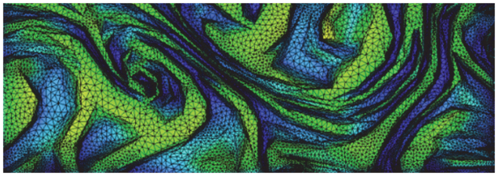

Figure 6
Result of a heat transfer simulation using Autodesk CFD. Mario Baio & Linus Birkendahl

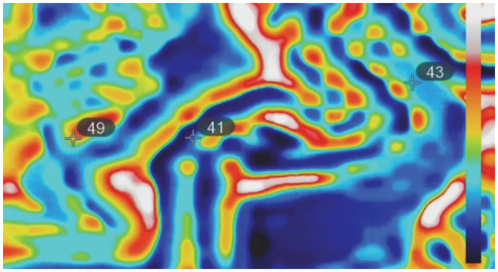

Figure 7
Evaluating the thermochromic response using a handheld infrared camera. The distinctive heat signature of each panel is informed by the design process and heat transfer simulations. Catalina Tripolt & Viktor Moosmann

Thermochromics
Thermochromics are materials that reversibly change colour depending on temperature (Seeboth & Lötzsch, 2013). Such materials are available in a variety of products. For the course, liquid crystal thermochromics were used. The material was provided by the department and applied by the workshop to ensure both a consistent coating of all eight panels as well as to comply with health and safety.

Fabrication
The CNC-milling of the topographies was organized by the course leader. Students submitted their CAD files. The contributions were then assembled in one file and handed over to the workshop which executed the milling. The designs were digitally fabricated from MDF using a three-axis CNC mill. After milling, all panels were sanded by the students and consequently primed white. Each of the eight idiosyncratic panels was then treated with a variety of fabrication techniques to achieve complex patterns (Table 1). After this individual phase, the panels were collected again and then coated with thermochromic ink by the workshop.

Testing and learning
The resulting chromogenic composites were documented and analyzed using photos and infrared thermography. Referring to Kolb's learning cycle from the introduction chapter, the learning process was enhanced by always comparing two dimensions (Haak, 2021). For example, feeling and thinking or watching and doing. This created links between the different stages of the course as well as allowed students to use iterative testing and designing to develop their projects.

RESULTS
In terms of design and fabrication, the eight student groups designed and fabricated eight idiosyncratic prototypes. Each group successfully implemented the tasks outlined in the brief and found individual project foci.

Eight projects
The seminar's participants created eight prototypes by the end of the course: one per group. Each group had individual research foci that were investigated using applying a variety of fabrication techniques (Table 1) (Figure 8). The goals can be roughly allocated to four categories: predicting the material response with simulations, precise fabrication, controlling different color changes, and mixing solid and fluid materials.

Learning outcomes
The seminar's results showed that the three techniques (simulation, material, fabrication) can help to introduce eco-relevant technologies to design education. The use of smart materials such as thermochromics has proven to be engaging and exciting. During feedback and evaluation, it was highlighted that the dynamic change of tolerances and resolution with each tool was a big challenge for the students. Accepting lower resolutions for milling

Table1
The eight projects include research foci and fabrication techniques.

	Foci	Technique
1	Transparency and fluid flow	cnc-mill, laser cutter, water pum
2	Cavity saces and undercuts	cnc-mill, 3d-printer
3	Layering and topography	cnc-mill, laser cutter
4	Topograhy	cnc-mill
5	Material density and channels	cnc-mill, different salt solutions
6	Multi-material inlays	cnc-mill, 3d-printer, metal inlays
7	Chromatics and topograhy	cnc-mill, multile coatings
8	Perforation and topography	cnc-mill, drill

Figure 8
A perforated thermochromic panel (8) was heated up using a conventional hairdryer. Luis Navarro, Amy Ehringer & Kurt Brennecke

to save time conflicted with the student's ambition to produce prototypes that are as close as possible to the digital design. The students understood the relevance of the digital simulations for the design process, and it allowed them to plan the material response.

Adapting the mesh geometries for the heat transfer simulations was similarly challenging. The difference in NURBS and mesh files in this context was new to even some of the more experienced students. Adapting geometries for each stage of the process conflicted with some entrenched paradigms concerning the inherent accuracy of digital models. This allowed students to gain new perspectives regarding accuracy and precision.

DISCUSSION

The results show that the course has been successful in a series of aspects. The students engaged with the subject and the taught techniques independently. When asked, they stated that some had previously been exposed to environmental simulations in other courses but that the seminar made them appreciate the tangible nature of working with smart materials.

Critical reflections

Concerning the five characteristics previously defined, a few comments can be made (Cross, 1999). How to engagingly teach environmental simulations has been identified as a *purposeful* investigation. The students have acquired new knowledge since the tasks promoted *inquisitive* experimentation. By asking the students to study and present previously published, relevant research ensured that their experiments were *informed*. Since the students had to A) follow a rigorous list of tasks, and B) plan their steps the experimentation process was *methodical*. The final submission consisted of a PDF brochure documenting the experiments and results. A broad variety of graphic representations satisfied the *communicative* criteria. (Figure 9)

Reflecting on the seminar, a series of improvements for future courses were identified by the author.

- The tasks must be clearly defined and explicitly state each step's desired outcome.
- The digital environmental simulations require a lot of support and time.
- The role of smart materials as an engagement tool rather than a technical requirement must be communicated more clearly.

Limitations

Two sets of limitations have been identified. The first set consists of structural limitations such as workshop availability and restrictions on time spent due to a low number of credits for the course. The second set of limitations is concerned with the transition of knowledge from research to teaching. The taught methodology has been previously developed by the author/teacher and specifically adapted for teaching. The biggest challenge has been the compression of years of experience with digital environmental simulation software into two input sessions.

Future potential and curricula implementation

Further potential exists in intensifying the computational methods to predict and design the material response. While this seminar relied on digital heat transfer simulations to predict thermal mass performance, future studies could emphasize the use of data for design. Some results show potential in this area. (Figure 10)

In addition to the positive effects on the design processes this approach, in some cases, also took pressure away from production. Projects that had a strong computational side before fabrication tended to be bolder when producing the prototypes. The research was not able to identify whether this was due to higher ambition because of promising results in detail, or if it was because the digital results counted as much as the physical ones in terms of marking criteria. Regardless of which hypothesis is true, more intensive utilization of computer graphics and procedural design appears the logical next step.

This also applies to the potential of the method for implementation into future curricula for environmental design. As listed in the Introduction, smart materials, prototyping, and simulations are already in use across a variety of programs and schools. Moving forward, one can see combinations of those methods being applied in environmental design classes as well as computational or fabrication skilling modules. This would be in line with an increasing demand for cross-/multi-/inter-disciplinary courses that link technical skills with environmental agendas. This can help to further strengthen the overlaps of design and technology in the context of materials, simulations, and environments.

Figure 9
A selection of panels from the seminar. Each prototype differs in theme and technique.

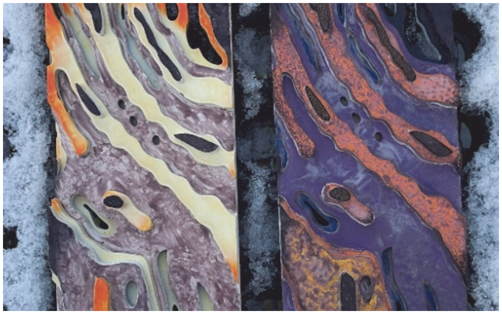

Figure 10
Scale tests (3d-prints) coated with thermochromic ink. The cooling effect is induced by snow. Students had to be inventive during lockdown phases due to Covid-19. Catalina, Viktor

Student feedback

The students' post-seminar feedback holds valuable information about how to improve such a seminar. When asked, the students stated that they have greatly enjoyed the fabrication part. The simulation tasks were complicated and should be taught more intensively compared to the experimenting which appears to be easily done independently. The anonymous evaluation showed that the students perceived the course as engaging and well-structured but criticized the workload. As a response to this, it appears promising to test the method within design modules which tend to cover more credits and therefore allow for a more ambitious research-driven course design.

CONCLUSIONS

Digital simulations and material experiments can be used to configure the thermochromic response of architectural surfaces. The seminar's outcomes suggest that a cyclical understanding of learning (Haak, 2021) has the potential to design engaging courses that teach architecture students relevant technical skills in conjunction with design exercises. The diversity of prototypes allowed students to develop individual foci and to explore a variety of techniques through design research. The combination of three aspects (simulation, material, fabrication) can help to introduce eco-relevant technologies to design education. The knowledge acquired through this material-focused process could transfer to the architectural design process in two ways. First, in the form of tool skills that can be applied such as simulation and fabrication. Second, in the form of a general approach to design that includes material and environmental considerations to articulate architectural surfaces. Both the outcomes and the course design itself were reviewed to better understand the co-creation process of the three aspects. This evaluation provided a rich pool of ideas to mix various technologies for innovative environmental design and articulation in architecture.

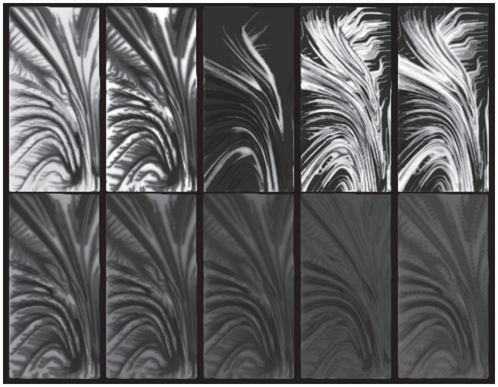

Figure 11
Procedural design techniques were used to generate some of the patterns and to predict the thermochromic response. Julian Edelmann & Mortiz Riedl

AUTHORSHIP INFORMATION

The post-graduate technical seminar *SE Neue Technologien* was held during the winter semester 21/22 at the *Institut für Experimentelle Architektur – Hochbau* at *Universität Innsbruck*. The author compiled this paper, developed the brief, taught the seminar, and provided all the teaching materials. Seventeen students participated: *Moritz Riedl, Julian Edelmann, Peter Kammerlander, Martin Danler, Aida Issakhankyzy, Johannes Resch, Mario Baio, Linus Birkendahl, Melvin Krier, Johannes Brübach, Micha Schneider, Catalina Tripolt, Viktor Moosmann, Amy Ehinger, Luis Navarro Preuß, Kurt Brennecke,* and *Tobias Hinterschwepfinger*.

ACKNOWLEDGEMENTS

The materials used for the fabrication of the student projects have been supplied by the *Institut für Experimentelle Architektur – Hochbau* led by *Marjan Colletti*. The panels were cnc milled and coated at the *Architekturwerkstätte* at *Universität Innsbruck* under the supervision of *Ernest Hager*.

REFERENCES

Addington, D.M. & Schodek, D.L. (2005). *Smart Materials and Technologies in Architecture*. Burlington: Elsevier.

Autodesk (2021) *CFD Ultimate* (Version 2021). Autodesk.

Burry, J., Salim, F., Williams, M., Pena de Leon, A., Sharaidin Kamil and Burry, M. et al. (2013). 'Understanding Heat Transfer Performance for Designing Better Facades', in *Proceedings of ACADIA 2013*, pp. 71-78.

Chronis, A., Dubor, A., Cabay, E. and Sadeghipour Roudsari, M. (2017). 'Integration of CFD in Computational Design', in *Proceedings of eCAADe 2017*, pp. 601-610.

Cross, N. (1999). 'Design Research', *Design Issues*, 15(2), pp. 5–10.

Cupkova, D. and Promoppatum, P. (2017). 'Modulating Thermal Mass Behavior Through Surface Figuration', in *Proceedings of ACADIA 2017*, pp. 202-211.

Cupkova, D., Byrne, D. and Cascaval, D. (2018). 'Sentient Concrete: Developing Embedded Thermal and Thermochromic Interactions for Architecture and Built Environment', in *Proceedings of CAADRIA 2018*, pp. 545-554.

Ghoshdastidar, P.S. (2004). *Heat Transfer*. Oxford University Press: Delhi, Oxford.

Groat, L. and Wang, D. (2013). *Architectural Research Methods*. 3rd edn. New York, Chichester: Wiley.

Haak, E. (2021) *Learning Cycle*. Inchainge Knowledge Base. Available at: https://inchainge.com/knowledge/experiential-learning/learning-cycle/ (Accessed 8 February 2022)

Körner, A. (2019). 'Thermochromic Articulations', in *Proceedings of ACADIA 2019*, pp. 332-337.

Körner, A. (2021). 'Thermochromic Animation', in *Proceedings of eCAADe 2021,* pp. 453–462.

Kretzer, M. (2017). *Information Materials.* Cham*:* Springer.

Lally, S. (2009). 'Potential Futures', *Architectural Design*, 79(3), pp. 88–97.

Lampert, C.M. (2004). 'Chromogenic Smart Materials', *Materials Today*, 7(3), pp. 28–35.

Lynn, G. (2010). 'From Tectonics to Cooking in a Bag' in Lynn, G. and Gage, M.F. (eds.) *Composites, Surfaces, and Software.* New York, London: W.W. Norton, pp. 19–24.

Marble, S. (ed.) (2012). *Digital Workflows in Architecture*. Barcelona: ActarBirkhäuser.

Moholy-Nagy, L. (1968). *Von Material zu Architektur*. Florian Mainz: Kupferberg.

Perez, G., Allegro, V.R., Corroto, M., Pons, A. and Guerrero, A. (2018). 'Smart reversible thermochromic mortar for improvement of energy efficiency in buildings', *Construction and Building Materials*, 186, pp. 884–891.

Peters, T. and Peters, B. (eds.) (2017). *Computing the Environment*. Hoboken: Wiley.

Phillips, S.J. (2017). *Elastic Architecture*. Cambridge: MIT Press.

Roberts, A. and Marsh, A. (2001). 'ECOTECT', in *Proceedings of eCAAde 2001*, pp. 342–347.

Rousseau, P. (2021). *Digital Pedagogy*. University of Toronto Libraries Research Guides. Available at: https://guides.library.utoronto.ca/digitalpedagogy (Accessed 22 December 2021)

Seeboth, A. and Lötzsch, D. (2013). *Thermochromic and Thermotropic Materials*. Pan Stanford.

Vaidya, A. (2020). 'Teaching and Learning of Fluid Mechanics', *Fluids*, 5(49).