

DESIGN SCIENCE LABS

Why architectural research needs laboratories for integrated and networked simulation

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Abstract. The ever increasing complexity of architectural projects demands efficient tools to assist within their associated design processes. We present an infrastructure initiative to tackle these challenges with Design Science Labs that are heavily rooted on simulation techniques in various academic fields. The merits of these techniques are discussed under the prospect of research and teaching experience as well as practical applicability. For an increased benefit, strong interoperability between these simulation techniques is desirable, but still not easily achievable. The infrastructure initiative aims to build smooth bridges between these fields and to gain additional architectural design space from their interaction.

1. Introduction

This paper describes an infrastructure initiative of our university aimed at setting up a network of research laboratories that enable the integration of state of the art simulation methods into the architectural design process. The basic premise of the initiative is that the architectural profession needs to start thinking big in its approach to research and to scientific methods.

While traditionally architects were content with studio space as their working environments, we argue that it's time architects take to developing their design work in close collaboration with specialized research laboratories. Given the complexity architecture inherently possesses and the ever increasing societal demands new constructions need to fulfill, architects

have no other choice but to become very professional about their working methods. The close coordination and integration of various types of simulation methods into the design process is a key aspect of this. In fact, the collaborative interdisciplinary teamwork from the earliest stages of design has long become standard in international competitions. Yet, despite occasional examples of the contrary, adequate laboratories that would allow to conduct and research similar design strategies in academia are still largely missing in most architecture schools.

An inspiration for this integration of scientific processes into the design practice is Buckminster Fuller, who coined the term design science, defining it as *“the effective application of the principles of science to the conscious design of our total environment in order to help make the Earth’s finite resources meet the needs of all humanity without disrupting the ecological processes of the planet.”*

The integration of simulation methods into the design process has been a constant subject of CAAD research over the past 30 years at least (Augenbroe and Winkelmann 1991; Chaisuparasmikul 2006; Flemming and Mahdavi 1993; Mahdavi et al. 1997; Maver 1988). While advances in physical based simulation methods have improved dramatically in certain fields, leading to entirely new subdomains in building design, the integration of these specialized domains into the design process is still unsatisfactory, despite the fact that the notion of building performance and energy efficiency are currently getting a lot of public attention (Cody 2005). The initiative put forward here differs from earlier work in that it puts its focus not so much on the development of unified standards and more coherent or more powerful software packages, but on establishing smooth collaborative processes between the individual laboratories. Furthermore the labs are based on a notion of performativity that goes beyond physically based digital simulation to reflect also the cultural and social aspects of design (Kolarevic and Malkawi 2005; Hauser 2005). Thus we believe that the issue is best addressed by networking spaces and people, not just by developing new software (although that remains an important part of it).

The rationale for this undertaking as well as the outline of its implementation is described in the following sections. Since simulation is a central part of the present project, we provide three general arguments how the architectural practice may take advantage of it in Section 2. The most useful fields of application are particularized in Section 3. The relationship between digital and analogue simulations as our approach in the design science labs concept, as well as a brief description of the individual laboratory setups is discussed in Section 4. Our proposed approach to achieve interdisciplinary connections and exchange mechanisms between these labs is outlined in Section 5.

2. Why Simulation in Architecture?

The simulation of a process means to synthesize a model that incorporates most of the characteristics of the original process. There are several reasons why simulation is important for architects.

- *Enhancement of creativity*: The creation of new and original solutions to a given problem is an iterative process. It depends inherently on the feedback that comes from the actual exploring of successive development stages. Building physical realizations of each design step is expensive and cumbersome. With simulation, new solutions to existing problems can be explored without having to spend money for physical realizations of any intermediate development stage. Furthermore, the feedback parameters may be difficult to obtain by hand (e.g. energy consumption, sociological quality, structural cost,...). With simulation, these project descriptors are readily available and the designer can learn from the outcome, which may in turn lead to improved solutions.
- *Building safety*: Building regulations may preclude certain architectural forms due to their inherent dangers. For example, fire regulations may prohibit open office spaces connected to an atrium, because the smoke may flow into the atrium and render fire exits unusable, which may be located there. However, with simulation, the flow of smoke becomes accurately predictable and hence it can be shown if an architectural form provides enough safety for its users.
- *Optimization* is an algorithmic enhancement to the design process, made possible via simulation. In the present context it can be useful in one of two aspects: (a) finding solutions which nobody may have come up with before and (b) allowing a design process to be guided by physical principles.

The *first* aspect is associated with genetic search strategies. As a suitable mathematical analogy, complex architectural problems can be described as a multi-parameter and non-convex problem. Although mathematically not simple, standard algorithms are available for this type of problem. Then, in conjunction with a simulation, genetic search algorithms can help to find architectural solutions that were not investigated before for various reasons.

The *second* aspect of optimization is associated primarily with 'Topology Optimization'. It helps to initiate an automatic design process that leads to structures which resemble natural load bearing structures like human cortical bones (for further details, see Sec. 3.5).

3. Important Fields of Simulation

3.1. LIGHTING

Lighting simulation has always been of interest for architects because it allows to create certain moods, which can not be designed just by the organization of the building structure. One of the first simulation tools was 'Radiance', which allows for quite realistic estimation of the lighting results. It achieves its results by using a hybrid approach of Monte-Carlo and deterministic raytracing. Thereby, the calculation of light transport is divided into three main parts: the direct component, the specular indirect component, and the diffuse indirect component (which became later known as the 'radiosity'-method). Although this leads to good results for many standard situations, it fails for a number of special cases, e.g. heliostats or parabolic light fixtures.

On the other side, an armada of accelerated rendering software was developed, that built solely on raytracing. Although it proved much faster, pure raytracing ignores diffuse reflections. Many workarounds were developed but none of them yielded physically accurate lighting results.

Some time ago, an algorithm called 'Metropolis Light Transport' method was developed (Veach and Guibas 1997). It provides un-biased, hence physically accurate results and is implemented in the commercial renderer 'Maxwell'. Hence, both Maxwell and Radiance represent useful tools for realistic lighting simulations.

3.2. FLUID DYNAMICS

Fluid dynamics can be subdivided into hydro- and aero-dynamics (dealing with the flow of water and air, respectively). Both fields are relevant for architectural projects (Chen and Srebric 2000). Hydrodynamic applications are, for example, the development of projects in a flooding area. Another application is the analysis of the flow of rain water over the free form surface of a building. The outcome can be used for technical reasons or to make an aesthetic statement.

Sample applications for aerodynamic analyses are: the structural integrity due to wind loads, the production of sounds from vibration of façade elements, the reaction of moving elements to wind as well as energetic aspects such as ventilation.

To summarize, fluid dynamics allows us to analyze the interaction between an architectural project and the fluids around it. Previously, this analysis was carried out in wind channels which were expensive to operate. Nowadays, in many areas, the use of wind channels has been superseded by 'Computational Fluid Dynamics' (CFD). Thereby, the flow is simulated via the solution of the Navier Stokes Equation on a mesh of finite elements.

Although the method demands a lot of CPU time, it is much more affordable than wind channels. An additional advantage is that the digital architectural model is directly amenable to automatic optimization.

The major software players in this field are 'CFX', 'Fluent' and 'Star-CD'. However, they have a steep learning curve and require a broad fluid dynamical background. Hence, we have developed an in-house application that utilizes a standard-CFD-core and a graphical user interface that is tailored to the needs of our architectural practice and teaching requirements (see Figure 1).

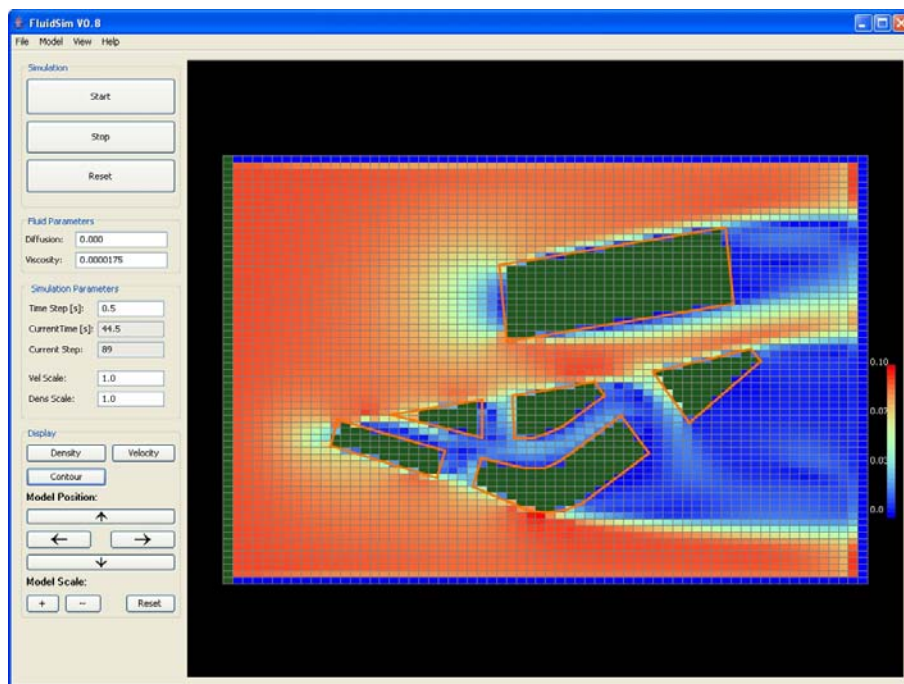


Figure 1. Computational Fluid Dynamics (CFD) application used for teaching. It shows the wind velocity distribution around clustered office buildings.

3.3. BUILDING ENERGY SIMULATION

Due to rising energy prices, the accurate management of the energy consumption of buildings has received major interest in recent years. In several countries even the legislation demands certain energetic criteria to be satisfied, before a project can be built.

Another important application tightly related to building energy simulation is the control of the micro climate in buildings. This becomes increasingly important for large rooms such as open office spaces or atria.

Especially in a high atrium, the temperature gradient from floor to floor is a natural phenomenon, but may be undesirable. The simulation and control of this effect is possible with the appropriate tools.

One of the most widely used tools in this field is 'EnergyPLUS', developed by the Lawrence Berkeley National Lab (Crawley et al. 2000). It is based on its predecessors DOE-2 and BLAST, which both have been verified over a long time on many large scale projects. Another application, more in use for climate control, is the software 'HevaComp'.

3.4. SOCIOLOGICAL ANALYSIS

The prediction of the sociological impacts of architecture is likely the most difficult one. A way to deal with this problem was developed by Bill Hillier. It is the well known 'Space-Syntax', which represents a scientific methodology to assess certain sociological aspects of architectural spaces (Hillier 1997). The method is currently used with great success to design spaces which reduce the crime rate, offer great communication qualities as well as many other aspects.

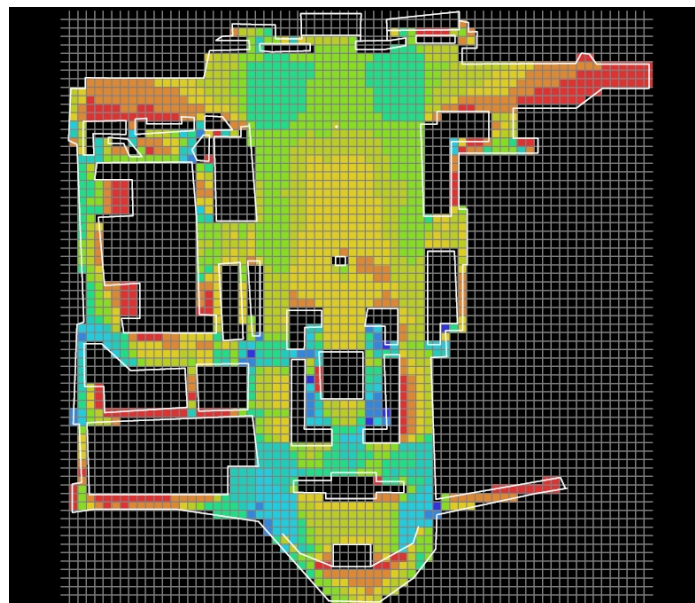


Figure 2. Sample results of the sociological analysis of 'Tiananmen Square' (Place of heavenly peace, Beijing, China). A specially designed Space-Syntax analysis teaching software was utilized.

One major drawback of the method is that it is currently only available in 2D. Hence, for city topographies built on hills (e.g. San Francisco), the

actual sightline differs significantly from the sightline in a 2D-projection. The specially designed teaching software we are using (see Figure 2) can consider arbitrary 3D topographies.

3.5. STRUCTURAL AND TOPOLOGICAL ANALYSIS

The analysis of structural integrity was probably for a long time the most important one in architecture. Elementary statics are idealizations or simplifications of the real structure. These methods were used until the rise of the 'Finite-Element-Method'. It helps to solve any physical problem up to a certain precision, which solely depends on the discretization (grid size). Consequently, it allowed the secure construction of many free form shapes that could simply not be analyzed with elementary statics methods.

Another very important aspect of structural analysis is known as 'Topology Optimization': in conjunction with an evolutionary optimization method, the structural analysis can be used to guide a design process that leads to optimal load bearing structures (Wang M.Y. et al. 2003). The resulting structures resemble human cortical bone or other natural load bearing structures. They offer the best possible trade off between structural integrity and mass.

In general, topology optimization is mathematically very complex and the available commercial codes (e.g. 'Tosca') have a steep learning curve. Hence, for teaching and in-house-use, we have developed an application that hides much of the complexity but delivers an excellent quality of structures (see Figure 3).

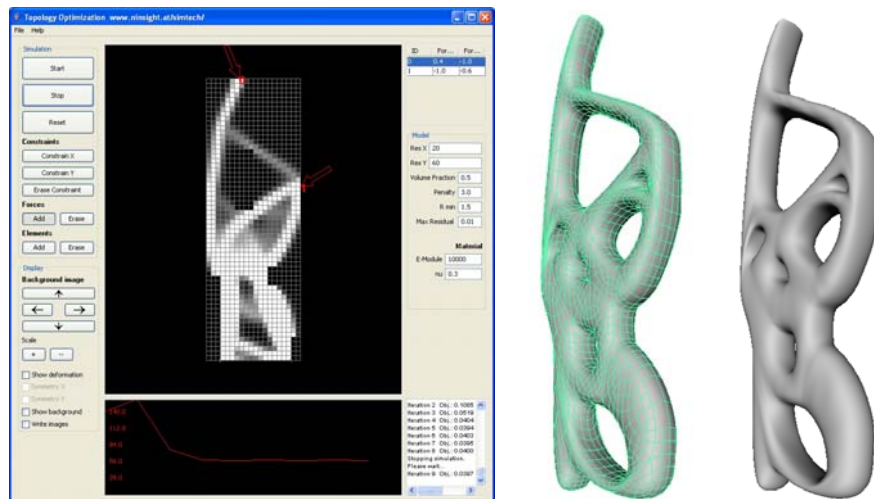


Figure 3. Teaching application used for topological optimization (left). A given set of boundary conditions (loads, constraints, material parameters) leads to an optimal load bearing structure (right).

4. Design Science Labs

4.1. DIGITAL VS. PHYSICAL MODELS AND ENVIRONMENTS

In Section 3 we outlined the most useful fields of application for simulation methods in architecture. Common to all methods mentioned in that section is that when the necessary software and the appropriate project data is available, they can be carried out on standard computers. Thus, the outline in Section 3 is based on the tacit assumption that simulation in architecture is equivalent to digital simulation. Given the widespread availability of computers in architecture schools, one might question the need for dedicated laboratories. As a matter of fact, the notion that digital simulation is the future and that the integration of the different simulation methods and domains will happen naturally in software rather than in a laboratory space is a basic premise of many research approaches about architectural simulation. In this section we challenge this notion. Simulation in architecture cannot and should not be limited to digital methods. Rather, a broader, more holistic approach to simulation must take physical models as well as digital models into account.

The main reasons for this are the following:

- *Tactility of physical models*: To this day physical models are seen as important ways to explore the architectural qualities of unbuilt projects. Despite the advances in computer graphics and the easy availability of realistic renderings and walkthrough simulations one has become accustomed to, physical models have not disappeared from the architecture studio. On the contrary: digital tools such as 3D printers and laser cutters have created a tendency towards producing physical models more frequently and of higher quality. Physical models can be immediately understood, they give a reliable sense of scale and they have tactile qualities no digital model can possess.
- *Physiological effects of light*: As mentioned above, physical based simulation of light leads to reliable data about light density and distribution and can also reliably predict the look of lighting solutions for both natural and artificial light. But they are not capable of sufficiently exploring the physiological and psychological reactions of humans to certain light conditions. Therefore these important aspects of lighting design can only be studied through tests with actual lighting fixtures at 1:1 scale. These physical tests help to complement the results we get from digital simulation.
- *The psychology of human movement*: We know very little about the intricate ways how people's movements in the spaces architects design for them are influenced by how they are designed. When the human interaction with work spaces or living spaces needs to be

assessed in more detail (because of safety hazards, space limitations or simply because novel solutions are tried out) common ergonomic standards or guidelines often are not sufficient. Especially if such assessments are not seen as purely biomechanical, but try to take the psychological aspects of human movements into account, they can only reliably be done by tracking the physical movement of a human body. Tracking systems such as the one we installed in our media lab enable this type of simulations. Furthermore they can be used to experiment with gestural interaction in Virtual or Augmented Reality.

- *New materials*: For new types of materials, often times sufficient data for digital simulations are not available. Simulating their behavior in real world applications thus requires that physical prototypes be built and tested. One of our labs is set up to specifically explore these topics, which are currently gaining greater importance in architecture (e.g. smart and responsive materials, see Addington and Schodek 2005).

As the above examples illustrate, there are many instances where analogue and digital technology must be combined in order to achieve a holistic simulation. This need for both digital and analogue methods is a central aspect of the approach we took in conceiving the design science labs initiative.

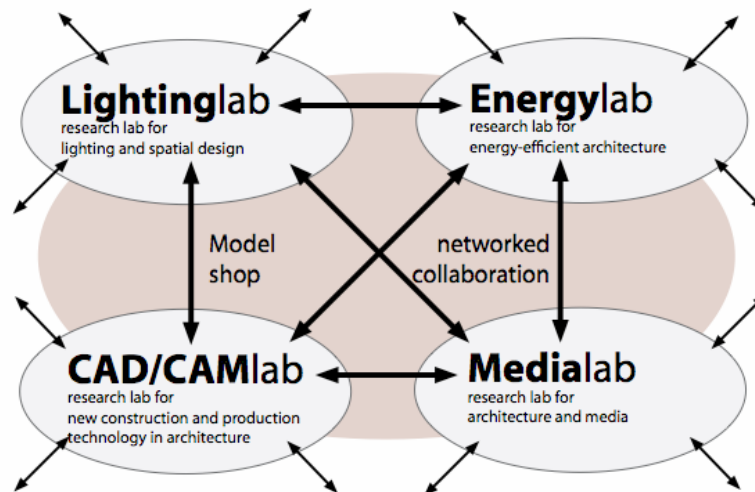


Figure 4. Diagram of the four labs realized as part of the first stage of the TU Graz Design Science Labs initiative.

4.2. DESIGN SCIENCE LABS, FIRST STAGE

In its first stage of development the Design Science Labs (DSL) initiative comprises four labs: an energy lab, a lighting lab, a CAD/CAM lab and a media lab. All four are networked and share computing resources as well as facilities for creating physical and digital models.

Not all of the labs are situated in the same building, which on the one hand is not ideal as it limits personal interaction between the lab staff. On the other hand the separation led us to setting up and promoting digital communication methods. These will be addressed in the next section. Based on these modes of communication the future development of the DSL initiative can happen independent of the spatial constraints of any single existing building. The openness of the networked communication also allows for future growth: a structures lab, an urbanism lab and a landscape lab are planned for the next stage of development.

4.3. CAD/CAM LAB

The CAD/CAM lab is divided in two parts: it contains equipment to study the experimental use of new materials (such as foams, smart materials, textile concrete reinforcements etc.) in architecture. The other part is essentially a research database in which the results of these experiments are systematically gathered to be able to share it with partners inside and outside our university. The CAD/CAM lab is the brains behind our extended model shop. Besides standard analogue machinery for building architectural models and 1:1 prototypes the model shop contains various Computer Aided Manufacturing facilities, such as a CNC milling machine, a 3D printer, laser cutters.

4.4. ENERGY LAB

Methodically its emphasis is on computer simulation. Among others it will be set up to carry out the following evaluations: thermal simulations, multi-zone airflow simulations, comfort-evaluations, weather-data analysis, energy simulations, 3D Computational fluid dynamics, shadow studies, daylight and artificial light simulations. The lab is also equipped with various sensors and measuring devices to validate computational results in situ.

4.5. LIGHTING LAB

The lighting lab is situated in a very large (110m²) and tall (8m) dark space, set up to explore the effect of light colors ranging within the spectrum of daylight. It supports the use of state of the art technology for dynamic lighting control using the DMX protocol and a variety of peripheral media and software. The setup provides a wide variety of spots that can be easily

rearranged with a small crane. From a control-booth the physical simulations can be done in parallel with digital simulations on a virtual model. The lighting lab is situated next to the faculty's model shop, which makes it convenient to study the lighting properties of physical models and to study the interrelations of light and material.

4.6. MEDIA LAB

The media lab is an environment for simulating the augmentation of space with digital media. It contains an optical tracking system and an openly programmable set of sensors and advanced input and output devices (such as a head mounted display, high definition projectors and tablet screens) by which the lab's space can be turned into a reactive environment. Three main types of investigations are supported: The precise tracking of human movement as a way to simulate patterns of usage and action of a (virtual) space; gestural interaction with different media as a way to simulate new types of spatial user interfaces and hybrid environments; and immersive modeling to explore multisensory ways of creating and interacting with architectural form.



Figure 5. Media Lab for Augmented Architecture. The Lab contains an optical 3D Tracking System and an openly programmable set of sensors and advanced input and output devices (such as a head mounted display, high definition projectors and tablet screens).

5. Networking of the Labs

Usually, it is difficult to transfer data from one simulation application to another one. The reason is that the process is equivalent to transferring the problem from one physical idealization to another one. For example, for a lighting simulation, the thickness of the wall is irrelevant, while for an energetic simulation it is most relevant. One way to overcome these problems is to use a common building model that can incorporate all possible physical domains. Similar strategies are used with great success in mechanical engineering practice. However, for architectural applications, such a strategy does not yet exist.

In the case of the Design Science Labs initiative, this problem is made even more complex by the mix of digital and analogue procedures that are employed. If combining the different abstractions into one comprehensive model in the digital realm appears to be difficult, the hybrid analogue/digital nature of the approach taken in our labs makes it impossible. So what do we refer to if we call the labs networked?

5.1. PRAGMATISM

Finding a one-size-fits-all format suitable for the description of a common building model might be possible one day, but for the time being it seems more practical to adopt a more pragmatic strategy that tries to adjust the means to the ends.

The problem of course is to know beforehand which simulations do and which ones do not yield any useful results. So the idea we adopt in the DSL labs is to develop a strategy for finding and documenting best practice approaches for different design tasks and to share these among the labs.

5.2. ONLINE ENVIRONMENT: BEST PRACTICE AND PEOPLE

Software licenses and computing resources are shared online in the local area network of our university. Obviously the new Design Science labs are networked in this sense. On top of that, a web-presence of all individual labs will be established that includes information about the current set-up, regulations, user manuals etc. – all of this, of course, is just common sense.

Beyond that, we are planning to set up an online database on which all users can save and document their simulation work. Based on experiences we have gained using our online environments for creative collaboration in teaching we hope to be able to set up an environment common between all four labs in which students share and discuss their simulation work. Over time this database will become a case base new users can turn to in order to see what's been done before and what's possible with the different methods and means available in the labs. Furthermore these online environments can

be analyzed to derive best-practice models for different tasks based on user preferences and experiences. Especially when people work on their projects in more than one lab in parallel, the synergies between different types of simulations will become manifest.

In the end one of the strongest arguments for setting up actual laboratories, spaces that people go to for special types of investigations, rather than just providing specialized software, is not only the physical infrastructure needed for some simulations. It's also the specialized expertise of people that one can find in those spaces. The online database will make it easier to find experts based on the prior work they have done. But the labs are the places where these experts can get together, where the knowledge and expertise about these topics that are so important to architecture can be developed.

6. Conclusion

“[...] With an inventory of available resources in hand, the next step for a designer is to use it well. Comprehensive anticipatory design science demands maximum overall efficiency with the least cost to society and ecology. Being comprehensive is a direction that implies extensive, omnidirectional research. [...] The goal is to optimize, rather than compromise.” Buckminster Fuller (quoted from Baldwin 1996, p.62)

In this paper we gave an overview over the Design Science Labs, a recent infrastructure initiative at our university. Its goal is to make scientific simulation methods an integral part of architectural design processes. We argued that, while this has been a topic in CAAD research for a long time, and is currently getting a lot of public attention in international competitions, the topic has not been taken on by architecture schools in as big a way as it would deserve. By establishing laboratories for different distinct types of simulations which are set up to support a mix of analogue and digital methods as necessary, and by providing online support for creating a pool of best practice examples, the goal is to identify best practice approaches and to build up a network of experts and synergies between the individual labs.

At the time of this writing, only two of the planned four labs are in operation, while two more are scheduled to open next month. Nevertheless the initiative has already stirred a lot of enthusiasm and our faculty is likely to get funding for setting up the mentioned additional labs. Thus we will come closer to an environment that can foster a comprehensive anticipatory approach to architectural design. To what degree the synergies between the labs we anticipate will come about and how big the impact of the new facilities will be on design studio rather than just on research remains to be seen.

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