Digital Fabrication in Education

Strategies and Concepts for Large-Scale Projects

Philipp Eversmann
Eversmann Studio
studio@eversmann.fr

The consequences of automation technology on industry are currently widely discussed in terms of future tasks, work organisation and working environments. Even though various novel education programmes specialise in digital fabrication, relatively little has been written on concepts for a deeper integration of digital technologies in the architectural curriculum. This paper gives an overview of interdisciplinary educational approaches and digital project development techniques and describes a teaching method featuring intensive collaboration with research and industry, an iterative teaching method employing digital production of large-scale prototypes and a moderated self-learning process. We describe two examples of teaching initiatives in particular that were undertaken at TU Munich and ETH Zurich and analyse their results in terms of physical outcomes, teaching accomplishments, resource efficiency and connection to research. We discuss the relationship between necessary teaching intensity, project size and complexity of digital fabrication equipment and conclude by giving an outlook for future initiatives.

Keywords: interdisciplinary collaboration, iterative process, self-learning

INTRODUCTION

While the age of “personal fabrication” - an analogy to the age of personal computers - was enthusiastically proclaimed (Gershenfield 2005), recent articles focus on analysing the jobs most likely to be replaced by algorithms and machines, calling for a new culture of lifelong learning to cope with constantly progressing technology [1]. Most architecture schools feature digital fabrication equipment (Hemsath 2010) and a number of them now offer one or two year programmes specialising in digital technologies, such as the EMTech at the AA [2], CITAs-
important historic interdisciplinary educational initiatives and current digital project development approaches and discusses an educational method featuring a highly collaborative environment of research and industry, an iterative teaching methodology of short, full-development cycles using digital fabrication (see figure 1) and an approach fostering self-organisation and self-learning of students. In the methods section, we present the general teaching method and describe two teaching initiatives regarding their organisation, concept, project tasks and interdisciplinary setting. In the results section, we analyse physical outcomes, teaching accomplishments, efficiency and integration into current research. In the conclusion section, we compare the two education programmes in terms of resources and resulting conceptual adaptations, discuss the study environment in relation to research and industry integration and conclude by showing possible future initiatives.

Interdisciplinary education, learning by making and digital project development

Even before digital technology existed, teaching at Bauhaus (Moholy-Nagy 2012) gives valuable insights on how arts, crafts, materials and fabrication methods could be placed as a basis for architectural education. Later, Frei Otto created experimental laboratories in which students and researchers from different disciplines were able to study and analyse structures using physical models and prototypes (Otto 1984), allowing new forms of social interaction. Since software and machines are likely to change rapidly over time, researchers discuss the applicability of teaching digital methods in practice in the future (Garber and Jabi 2006), also in combination with a project-based approach to technology (Bechtold 2007). The Maker movement (Dougherty 2012) has extended tremendous influence in education (Halverson and Sheridan 2014) and even industry (Ramsauer and Freissnig 2016). This concept of “Learning by Making” or also Constructionism (Papert and Harel 1991) has been further developed through the combination with digital technology (Blikstein 2013). Novel innovative teaching formats and work organisation strategies can also be found in related professions and research institutes: Students at the product development group at ETH Zurich are provided with standard mechatronics kits and access to rapid prototyping to allow complete product design cycles (Heinis et al. 2015). In software development firms, the traditional task of the “Software Architect”, who draws up a detailed structure of programme classes and their functions, is being increasingly replaced by a method called “Scrum” which favours self-organized teamwork instead of rigid organizational structures (Beedle et al. 2000). Realizing that all requirements cannot be specified up-front and con-

Figure 1
Students working with robots during fabrication of case-study project of the MAS Digital Fabrication at ETH Zurich
text and environment evolve during development
time, this method employs short development cycles
without predefined working processes. Studies high-
light that digital technologies can be more efficiently
taught using a “conducting” rather than “instructing”
teaching method (Sawn et al. 2000). Recognizing
the importance of interdisciplinary social interaction
on innovation, technology firms make large invest-
ments in working environments that encourage new
encounters and exchange of ideas [8].

METHODS
In this section, we introduce our teaching method-
ology and describe two examples of teaching initia-
tives. Our strategy was to place digital development
of large-scale prototypes with real construction ma-
terials at the centre of the educational programmes.
This provided us with the means to rapidly evalu-
ate not only the spatial and architectural qualities
of projects, but also to analyse the functionality in-
cluding material, fabrication and joining constraints.
The digital development was undertaken in short-
term iterative development cycles (see figure 2). Dur-
ing each cycle a full project development includ-
ing 3d models, digitally fabricated prototypes, struc-
tural concept, renderings, analytical sections, plans
and diagrams had to be delivered. After each cycle,
problems were meticulously analysed and new sol-
lutions, constraints and more detailed requirements
and analyses were integrated in following iteration
cycles. Considering the vast variety of materials,
their processing and joining possibilities and the lim-
ited amount of time available in our education pro-
grammes, we focussed on teaching a method of
how to acquire basic knowledge of material prop-
erties and directly explore digital processing, join-
ing and spatial possibilities. Instead of a traditional
teacher-centred approach, we promoted a moder-
atated self-learning process. Students worked in teams
which provided the possibility to self-organise and
adapt throughout the course of the programmes. For
both programmes, which we conducted at TU Mu-
 nich (academic year 2012/2013) and ETH Zurich (aca-
demic year 2015/2016), we created a study environ-
ment which allowed students to have multiple ways
of interdisciplinary social interaction. This was en-
abled by a series of common events, lectures, meet-
ings and discussion rounds with researchers, collabor-
ating professors and industry partners.

TUM studio einszueins
Organisation. Studio einszueins was established
through the guest professorship programme of the
architecture faculty of TU Munich. The programme
was organised by Philipp Eversmann in collaboration
with Philipp Molter at the chair of Architectural De-
sign and Building Envelopes of Prof. Tina Wolf. Studio
einszueins was integrated in the Master of Science
programme of TUM, and was attended by 26 archi-
tecture students. The programme was organised as
a design studio in two consecutive semesters, which
was necessary in order to fit in the Master’s curricu-
lum. Most of the students continued throughout the
whole year, which helped to establish a continuous
design process. We advised skills in 3d-modelling to
enter the studio, but no prior knowledge in program-
ing or digital fabrication was required.

Concept. We defined the development and realisa-
tion of large-scale prototypes as a central part of
the programme. Through this fabrication-integrated
design process, the students could deal with a va-
riety of processes between design and execution. In the course of the studio, we investigated various project organisation and development methodologies through digital means questioning existing design, planning and realisation paradigms. The students had to bear the responsibility for a planning process that dealt not only with the architectural aspects of a building, but also included financial and scheduling constraints as well as feedback between multiple project partners. We focussed on investigating digital fabrication processes through the development of new material applications and manipulation of production facilities. Through the integration of various industry partners, collaborating chairs and a client into our teaching activities, we created a social network in which a variety of interdisciplinary encounters were enabled (see figure 3).

**Design Project Development.** The students’ task was to create envelopes and structures for exhibition pavilions using digital fabrication processes. Even though the material choice was unrestricted, students had to verify feasibility with digital fabrication equipment. Through a competitive process, schemes for four different projects were developed in the first semester. Already at this stage, each team had produced multiple prototypes with the envisioned material, digital processing and assembly technology (see figure 4). The final realisation of the projects was made highly dependent on the students’ initiative, which was further enhanced through their direct contact to clients and collaborating firms.

**Industry Collaborations.** In order to allow knowledge transfer and experimentation with advanced fabrication technology a number of collaborations with local facade and material production companies were directly integrated in the programme. This enabled a range of external teaching activities and even an outsourcing of parts of the manufacturing processes. This allowed students to gain insights into the latest facade and structural design and fabrication technology as well as to develop their designs directly with technical inputs from renowned experts in the field. We organised a series of meetings, pre-

---

**Figure 3** Teaching network of studio einszueins: a multitude of interaction possibilities with collaborating chairs, industry partners and clients

**Figure 4** Prototype for the project “STITCH”, a double-layer curved-folded aluminium structure
MAS ETH Digital Fabrication

Organisation. The Master of Advanced Studies MAS in Digital Fabrication programme was organised as the central part of the teaching platform of the National Center of Competence in Research NCCR Digital Fabrication at ETH Zurich. It was hosted by the chair Gramazio Kohler Research in collaboration with the BLOCK research Group, the chair for sustainable construction and the ADRL Robotics Lab. The programme was organised by Philipp Eversmann (NCCR Head of Education), and Luka Piskorec. We selected 17 students with Master's and/or Bachelor's degrees in Architecture, Design and Engineering for the first class. The programme was conceived as a postgraduate programme for students who want to specialise in the field of digital fabrication. Prior knowledge in programming and digital fabrication was required and evaluated to enter the course.

Concept. The MAS was structured as a central design studio which was surrounded by a series of teaching modules. Necessary interdisciplinary knowledge as informatic programming, geometry, automatic sensing, robotic control, digital collaboration techniques, material processing and structural analysis was provided by the teaching modules, while hands-on experience with design and fabrication was practiced in the studio. The teaching modules clustered around three main study areas: (1) Computational Design, (2) Material and Constructive Systems and (3) Robotic Control and Fabrication (see figure 5). Teaching modules would typically last between one to four weeks, with the exception of the programming module, which was conducted throughout the whole year. The modules were organised as pieces of knowledge inputs provided by collaborating chairs, PhD-students and external guests relating to current design work. These inputs were deliberately not conceived as complete entities of a topic, but as basic nodes allowing the students to reach out to a range of resources for further self-study. Furthermore, we used the interdisciplinary network of the NCCR Digital Fabrication to create a dense social environment for the MAS students, researchers and professors through the organisation of a series of common activities, lectures and meetings.

Design Project Development. The students’ task was to design a double-story structure with a basic envelope as a minimal house using spatial robotic fabrication processes for timber construction. From the beginning, complete development cycles of
computational design-work up to full-scale robotically fabricated prototypes were effectuated. This allowed us to iteratively evaluate architectural as well as functional, material and constructive features for each cycle (see figure 6). In order to find a better ratio of design development and time for fabrication with the robots, and allow multiple design investigations, teams chose to regroup and adapt multiple times. Even though students were initially provided with a set of exercises of analytical and design work, the subsequent development strategy was developed and implemented together with the student team according to the current state of development, problems and external constraints. Through a lecture series, international guests were invited to not only give a presentation to an open audience at ETH, but also spend a day working with the students on their projects. This allowed the students to hear about valuable external views and to receive feedback on their design-work in the process.

Research Collaborations. We established the design and fabrication task of the design studio in direct connection to ongoing and future research. Already in preparation of the MAS, we conducted a collaborative research project on topological optimization of robotically assembled timber structures together with guest researchers from Aarhus University and Israel Institute of Technology (Soondergard et al. 2016). The development of our robotic fabrication process directly built on research of the NRP66 project “Additive Robotic Fabrication of Complex Timber Structures” (Zock et al. 2014). Furthermore, the development of the topic of spatially fabricated housing units provided a conceptual basis for the ITA-PhD research project “Architecture of Bespoke Modular Prefabrication”. Additionally, we encouraged NCCR PhD-students to provide mentorship to the students. This enabled MAS students to get in-depth understanding of research projects through helping doctoral students with demonstrator setups in exchange for technical counselling on their design projects. We also allowed students to pursue an independent research master’s thesis as well as realising a large-scale fabrication project. Furthermore, we were able to establish multiple industry collaborations for the realisation of the robotic setup and the final case-study project.

RESULTS

Physical Results

At TU Munich, we realised four large-scale prototypes in structural glass, aluminium, timber and polycarbonate. The projects were funded by collaborating firms and the organizers of the IKOM industry fair [9], who commissioned a demountable exhibition stand (see figure 9). Additionally, the projects were featured in two separate exhibitions at the Vorhoelzer Forum and the Bavarian Chamber of Architects in Munich [10] (see figure 10). At ETH Zurich, we were able to realize a robotically assembled double-story timber structure (see figure 8), which was used for the opening reception of the AAG conference in 2016 [11]. We are currently planning to present the structure again at the Zurich Design Biennale 2017 [12].

Figure 6
Multiple geometric configurations for the robotic assembly of timber structures: a double-layer reciprocal structure, discrete triangulations, spatial truss (used in the final project)
Teaching accomplishments

In both teaching initiatives, participants successfully developed their projects through multiple design cycles incorporating material studies, design development, digital fabrication processes and design validation through full-scale prototypes. Classes did not focus on specific software, but instead employed general digital design methods through visual programming or object-oriented programming in Python. Through the task of building large-scale projects, the students were confronted with a range of other topics such as material and structural analysis, management and organization, kinematics, simulation, digital sensing and robotic control. Each student was able to independently solve complex design tasks, and program digital fabrication tools as well as robotic arms accordingly. Furthermore, at TU Munich, diverse project development methodologies could be investigated in relation to digitization and automation. Students had the chance to act and perform as a “digital general contractor” (stand for the IKOM fair, see figure 8) to cooperate with external companies (“TWIST” - Lampart, Hundegger, “VITRINE” - Seele, BGT, see figure 9) and to conduct independent research projects (“STITCH”, see figure 4). Both teaching activities were showcased in documentary films [13, 14].

Teaching Efficiency

While a similar teaching methodology was used in both education programmes, the project size and complexity of digital fabrication equipment was different. At TUM, teams of 2-4 students worked on multiple projects with CNC-equipment, such as laser cut-
ters, 5-axis mills and cutting plotters; at ETH, a team of 8 students worked on a single project using robotic technology. This difference in team size and digital tools had a large impact on team organization, collaboration techniques, teaching focus, student evaluation, and intensity of teacher interaction. Digital workflows in larger projects and therefore large teams require a precise definition of responsibilities and protocols for each student. In comparison to a smaller team size, this can demand a greater intensity of participation of instructors until resulting work becomes efficient. More complex digital fabrication tools like robots also demand much more work in their initial setup in comparison to CNC-machines whose processes are already defined. The iterative self-learning process of defining tasks, protocols and also fabrication processes proved to be a valuable part of education for the students. The social interaction and learning with and from multiple team members can be an extremely efficient study method.

**Research Integration**

We established multiple collaborations with ongoing scientific research in both teaching initiatives. At TUM, the authors’ research of on curved-folding techniques for multi-panel shells could be continued through the development of a double-layer curved-folded structure (see figure 4) (Eversmann et al. in press). Similarly, research on the application of structural glass in computational architectural designs (Eversmann et al. 2015) was further progressed through a glass structure with joints that, too, were made out of glass. At ETH, results were published in online magazines [15] and multiple research papers are currently awaiting publication in peer-reviewed journals and conferences. The robotic setup, which was developed by the authors, featuring a fully integrated CNC-Saw, could be further integrated in a CTI-research project undertaken under cooperation with Swiss construction company ERNE.

**CONCLUSION**

Moderated self-learning can provide students with a method allowing continuous learning of digital fabrication technologies in architecture even beyond the educational programme. The realisation of large-scale prototypes through interdisciplinary networks with research and industry allow students and researchers to benefit through a variety of social encounters, enable interdisciplinary exchange and foster collaborative working. These interdisciplinary networks can be created on multiple levels, depending on the local opportunity to integrate the schools’ chairs and infrastructure, research and industry partnerships. The two examples of teaching initiatives show that a local difference in available fabrication equipment, material budget and integration in the school’s curriculum can be actively integrated in the teaching strategy: While integration with research and interdisciplinary exchange was highly encour-
aged by the nature of the NCCR Digital Fabrication and its funding principles and state of the art robotic fabrication equipment was made available, at TU Munich the studio profited immensely by collaborating with a cluster of local high-tech facade and material processing companies. Therefore, instructors need to carefully evaluate and weigh available infrastructure and the possibility for external partnerships.

**Integration of Research and Industry**

The integration of research and education can have a very positive impact on both sides. Researchers can realise demonstrators together with students at a much larger scale and higher level of detail. Students respectively profit from gaining insights in latest technology and can prepare for future doctoral studies. Furthermore, through the open and investigative approach and resulting work, new ideas can be generated for future research. The realisation of prototypes in educational programmes also allows partners to collaborate on a short-term project before engaging in longer-term research relationships. Teaching collaborations with industry and practice necessitate long-term planning coupled with short-term availability, which can make them very challenging to integrate in educational programmes. Once established, they can create a potent interchange for both the educational institution as well as the industrial partner. In return for their technical and material support, companies can profit from the high visibility that large-scale case-study projects can attract. In addition, novel applications of company-specific materials and fabrication equipment can be realised.

**Future Initiatives**

Current teaching programmes in digital fabrication still remain far from being conceptually completely integrated in the architectural curriculum. New initiatives could focus on integrating computational design and fabrication techniques already in the very beginning of architectural studies. Instead of pursuing an educational concept of specialisation on digital technologies, a novel and holistic approach to architectural education could allow a new generation of architects to conceive and develop computation and fabrication at the core of architectural production. Even though the teaching of higher level digital design concepts and advanced robotics might not yet be directly applicable in architectural construction, it provides students with a method and broad basis from which they can easily learn and apply specific digital tools and software in a future of rapidly progressing technology. New experimental education approaches similar to those used in product development and informatic programming can provide a framework and experimental breeding ground for new ideas and studies. Instead of passively reacting to upcoming industrial changes, a holistic approach to digital fabrication in education can provide architects with the means to shape and create ways in which these technologies can be used in the future of construction.

**ACKNOWLEDGEMENTS**


The **MAS Digital Fabrication** was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation. (51NF40-141853). The following students participated in the programme: J. Chenault, C. Shiu Lun, J. C. Remy-Maillet, J. De Carvalho Paixão, A. Dell’Endice, L. Gabor, M. Helmreich, K. Hochschuh, Y. Hsiao Wei, J. Medina Ibanez, I. Mirtisopoulous, P. Odaglia, F. Salvaliaio, F. Scotto, S. Tsafou, A. Zaytsev and N. Hoban. We would like to thank...
P. Fleischmann and M. Lyrenmann for their countless efforts in helping to create our robotic setup and Schilliger Holz AG, Rothoblaas, Krinner Ag, ABB and BAWO AG for their support.

REFERENCES

Bechthold, M 2007 'Teaching technology: CAD/CAM, parametric design and interactivity', Predicting the future—Proceedings of the 25th International eCAADe Conference, Frankfurt, pp. 767-775

Beedle, M, Devos, M, Sharon, Y, Schwaber, K and Sutherland, J 1999, 'SCRUM: An extension pattern language for hyperproductive software development', Pattern languages of program design, 4, pp. 637-651

Blikstein, P 2013, 'Digital Fabrication and 'Making' in Education: The Democratization of Invention', in Walter-Herrmann, J and Büching, C (eds) 2013, FabLabs: Of Machines, Makers and Inventors, Transcript Publishers

Dougherty, D 2012, 'The maker movement', innovations, 7(3), pp. 11-14

Eversmann, P, Ehret, P and Ihde, A 2017 'Curved-folding of thin aluminium plates: towards structural multipanel shells', Proceedings of the International Association for Shell and Spatial Structures, abstract accepted


Gershenfeld, N 2008, Fab: the coming revolution on your desktop—from personal computers to personal fabrication, Basic Books


Heinis, TB, Goller, I and Meboldt, M 2016, 'Multilevel Design Education for Innovation Competencies', Procedia CIRP, 50, pp. 759-764


Moholy-Nagy, L 2012, The new vision: fundamentals of Bauhaus design, painting, sculpture, and architecture, Courier Corporation


[3] https://kadk.dk
[7] https://taubmancollege.umich.edu