Design Research Based Method for Digital Fabrication Teaching

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The paper describes the application of a standardised teaching method of digital fabrication in architecture. The introduction formulates a pedagogical problem and addresses both methodological and praxiological aspects of the teaching process based on design research. Next, the process is illustrated with a description of three digital fabrication courses where the teaching method was used. The initial implementation took place in 2016 at Faculty of Architecture at Warsaw University of Technology. The author outlines the translation of theoretical work frame into teaching method, presents the course outcomes and provides a critical analysis of results. In 2017, a revised teaching method has been used two times, again at Faculty of Architecture at WUT and at Monash Art Design and Architecture. Both courses are described in a way analogous to the initial exploration. In consequence, the results of the same course conducted in different teaching, conditions are compared. In conclusion, the developed method is evaluated in relation to teaching outcomes.

Keywords: digital fabrication, pedagogy, teaching, design-research

INTRODUCTION
Digital architecture is not only an element of scientific discourse anymore. Digital design and manufacturing are increasingly important parts of professional practice. This, in turn, created demand and a market for digital architecture education. Today both theoretical and practical aspects of CAD/CAM are a common component of teaching curriculum in the majority of architectural schools. Indeed over the last decade, a number of schools around the world developed and now offer programmes dedicated to digital paradigm. One of the areas covered in these courses is digital fabrication: an area that, in recent years, became a core discipline for architecture and brings a promise of filling a gap between architectural idea its realisation. The gap between digital and physical which due to the undertaken projects scale remains bigger than in other design for production related fields (Slyk, 2012). As Oxman (2010) states ‘Fabrication is not a modelling technique, but a revolution in the making of architecture’ which by ‘creating a direct digital link between what can be conceived and what can be built through file-to-factory’ (Koleravic, 2003) allows to perceive CNC manufacturing as an actor informing the creative process, not mere a tool. As such it requires teaching strategies that go beyond the competence in CAM. Over the years countless pavilions and experimental structures exploring
aspects of digital fabrication have been designed and built. However, as some researchers noted (Hemsath, 2010; Eversmann, 2017) not much has been written about pedagogical methods and outcomes of those ventures. Moreover, it may be observed that often teaching in the discussed area is driven by individuals, digital practitioners pursuing their own research and design ambitions rather than integrated pedagogical agenda (Oxman, 2008). Finally, an analysis of Architecture for Society of Knowledge own and various architecture programmes experiences in teaching digital fabrication allowed to observe that on a regular basis only a fragmented knowledge and an incomplete skill set, required for a specific task, is being delivered to students: leaving them with limited theoretical and practical expertise to benefit from in their further studies and/or professional practice.

PEDAGOGICAL AGENDA AND METHOD
A task to solve the problem mentioned above was set up as a part of the revision of Architecture for Society of Knowledge teaching curriculum for 2015/2016 academic year. In general, this task was to be achieved by:

- covering a wide spectrum of topics, both theoretical and practical, related to digital fabrication in architecture (agenda),
- creating student-focused process of knowledge acquisition and transfer (method).

The first of these was built upon the aforementioned analysis of teaching curriculums and studies of topic-specific literature. The teaching objectives formulated in a process included;

- awareness of available digital fabrication technologies and their integration methods,
- knowledge of recent trends in the field of architecture and digital fabrication,
- awareness of digital fabrication techniques development trends,
- classification of digital fabrication techniques according to the material's method of treatment,
- ability to shape the concept of the prototype,
- ability of appropriate technique selection to fabricate an object,
- awareness of the principles of digital fabrication devices operation, data formats and control protocols,
- ability to prepare proper prototype fabrication documentation,
- development of methods for assessing effects of work.

Following an ambition to develop structured and replicable pedagogy, a design research method was adapted for teaching process. The teaching scheme, shown in figure 1, is based on three entities of design research context (Edmonds, 1999); actors (students), environment (architecture, digital fabrication) and artefacts (design) while knowledge acquisition techniques are built upon overlapping reflective, implicative and aggregative relationships between them (Horvath, 2007).

This three-element, three-relationship scheme is used as a framework for developing adequate teaching methods. After formulating the aforementioned pedagogical agenda each teaching outcome (skill, knowledge, expertise etc.) is positioned within a relating entity; actors, environment or artefacts. Next the relationships between these elements are established. This is done by answering if a particular element requires previous knowledge and/or if it is required to gain a new one. In effect reflective, implicative and aggregative relationships between all the desired teaching outcomes are defined.
Finally these are translated into different teaching modes, catalysed by matching an area and a form of the classes. Reflective modes are delivered in form of seminars, tutorials and lectures. Implicative modes in form of workshops and colloquiums and aggregative ones in form of laboratories and design studios. The delivery of these various class-types follows the same order reflective-implicative-aggregative. Within these class-types teaching areas are being covered is environment-artefacts-actors order.

**INITIAL COURSE IMPLEMENTATION**

The described pedagogical method was used for the first time in Digital Fabrication course at Faculty of Architecture at Warsaw University of Technology during 2015/2016 summer semester. The student group consisted of ten Architecture for Society of Knowledge master students, eighteen Information Architecture master students and five Erasmus exchange program students. During the laboratory part of the course, they created and worked in ten groups. The classes were conducted once a week over course of the whole semester, that is sixteen weeks. The majority of meetings were evenly distributed between the seminar and laboratory blocks, seven classes each. Two additional meetings were used for introduction class and workshop session that took place between the seminar and laboratory blocks.

**Course Overview**

The first seven weeks were devoted to construction of reflective knowledge about digital fabrication environment. The seven meetings took form of seminars. The seminars were devoted to different technical and material aspects of digital fabrication:

- modes of production - subtractive, formative and additive,
- materiality and processing - wood, steel, masonry and others,
- form representation and tectonics.

Every student had to present a 10 minute long in-depth case study for each of the above seminar topics. The presentations were followed with a quick question and answer session. Each class was then concluded by a moderated discussion. The second part was designed to trigger implicative processes. A single workshop classes consisted of a series of exercises. In the first one, students were given small sheets of paper with sentences describing tools, processes, materials etc. discussed during seminar part. Using the previously gained knowledge, students had to arrange these into materials/tools/methods matrix drawn on a pin-up wall (figure 3). In the second exercise participants were given another set, this time of blank sheets of paper. Students had to take turns and pin-up comments on various aspects of the matrix, creating SWOT analysis of discussed area. These two activities allowed to structure previously gained knowledge and verbalise of these parts of it which remained tacit. In the next exercise tutor, distributed among the students over a hundred A5 photographs of digitally fabricated architecture precedents. These had to be recognised from the existing matrix point of view and pinned in a proper area of it (figure 2).

In the final exercise, students were introduced to the classification of digital fabrication techniques as proposed by Iwamoto (2009); sectioning, teaselling, folding, contouring and forming. Following short discussion in sub-groups of four, students had to assign previous precedences to one of these techniques. The session closed with an activity introducing aggregative process. Each student sub-group
was given a visualisation of an abstract architectural scale object and asked to sketch/propose how it could be built using all five fabrication techniques, defining digital fabrication processes, materiality and tectonics.

Finally, during the last seven weeks a design/laboratory working method was used. The previously gained knowledge, hands-on experience with CNC tools and iterative design process were connected in aggregative teaching mode. The students, working in groups of four, had to enter recursive design-research workflow. Groups were asked to design an abstract 3D form fitting into 50x50x50cm cube. This step was followed by design of the whole digital fabrication process, including manufacturing of a prototype, of the designed object. During that part of the course meetings took form of progress report followed by discussion on design, CAD and CAM environment and fabrication processes. This allowed to prepare students for some difficulties they would have to face and resolve in the next steps.

**Outcomes**
The final outcomes of the course took the form of two artefacts;

- exhibition of twenty-seven digitally fabricated prototypes representing ten group designed objects (figure 4),
- thirty-three student-written short papers describing a critical overview of digital fabrication and their learning process.

From a pedagogical perspective, the proposed method allowed to transfer and consolidate digital fabrication knowledge during the seminar and workshops classes and verify it during the laboratories. Nevertheless, two main problematic areas were recognised;

- individual teaching outcomes - where due to a large number of students involved and differences in group designs, it became difficult to assess if knowledge was evenly distributed among the students,
- record of knowledge and innovation - where posters, digital models, and physical models were not enough to document nonstandard outcomes and knowledge acquired during the laboratory classes.

These issues were addressed during next Implementation of the scheme in 2016/2017 academic year.

**REVISED COURSE IMPLEMENTATION**
In 2016/2017 academic year a revised version of the Digital Fabrication teaching method has been used twice. The first implementation was at the Faculty of Architecture at WUT. It was delivered over sixteen weeks to eighteen students. Eight ASK master students and ten Information Architecture master students. The second ran at the Monash Art Design and Architecture where the course was offered as an elective studies unit opened to master’s students and final year bachelor’s students. It was delivered to twelve students over fourteen weeks.
Course Overview

The principles of the course have not been changed: the general structure, teaching method and sequence of delivery were employed. Nevertheless in order to address problem areas recognised after the initial implementation few elements of the course required rethinking. To solve the individual teaching outcomes issues two alterations were introduced. First a minor one. The number of students taking part in the course was reduced. More attention could be devoted to individual student learning process and outcomes evaluation of both individual and group work. Moreover the seminar part was condensed to just three meetings. Each of these being dedicated to one, of the above mentioned specific aspects of digital fabrication, with every student presenting during each session. An intense learning environment, which helped to keep the students involved. Finally this minor change in the delivery schedule provided additional time for laboratory classes. The workshop class was conducted without alterations.

A major change was introduced the laboratory part of the course. In the first implementation a lot of time was used for designing the 3D form itself. Naturally that limited the time for iterative development and fabrication processes. Different models posed various levels of complexity and challenge in the context of digital fabrication. As such it was difficult to verify the teaching outcomes. To deal with such issues in the revised course version, students were given the same 3D model to work with. The model was loosely based on the geometry of Cloud Gate by Sir Anish Kapoor. This particular geometry was chosen because it is constructed out of continuous concave, convex and saddle surfaces. That poses an interesting problem from the point of view of modelling, fabrication and assembly. In order to solve the aforementioned issue of learning limited skill-set each group had to go through the described process two times (figure 5). Each time using different design strategy, fabrication method and materiality to operate with.

The second area of change is related to the record of knowledge and innovation and careful control of knowledge acquisition during the course. While using different modes of delivery also different types of knowledge were created. This is represented in the scheme where knowledge flow, related to described in-class activities is mapped onto three entities of design-research (figure 6).

During the seminars the explicit knowledge took form of a database of students presentations offering in-depth overview of various technologies, materials and fabrication strategies. Moreover the author supplemented the uploaded material with additional comments, links and references clarifying some of the issues discussed during a class. Students have access to this resource shall they need it as it is stored on a Moodle site accompanying the course. At the same time a tactic knowledge, an understanding of digital fabrication environment has been achieved. During the workshop part, this intuitive understanding was verbalised with the creation of the knowledge matrix. Again, the matrix was photographed and uploaded to the Moodle site, students have access to it. Students gained an ability to see interconnectivity between various elements of digital fabrication processes and read these in architecture precedents. Their architectural vocabulary has developed, tacit knowledge. In the final design-laboratory part students put all of explicit and tacit knowledge to work in creative process. During aggregative activity a large amount of the knowledge is ad-hoc, consequences of creative explorations. Often it is being lost in the recursive design cycle or remains a know-how; practical tacit knowledge of an individual.
order to avoid that each group submits a final artefact. A booklet offering an in-detail description of whole creative process, a research report. Each design iteration is described through discussed elements of digital fabrication, technical and material exploration, etc. The booklets are uploaded on the Moodle site and accessible to students: giving them opportunity to learn from and reuse some of the developed solutions in their work or research.
**Outcomes**

The outcomes of both the courses took the form of three artefacts:

- Moodle database and knowledge matrix,
- exhibition of digitally fabricated prototypes, nine at Faculty of Architecture at Warsaw University of Technology (figure 7) and six at Monash Art Design and Architecture (figure 8),
- process report booklets, one for each prototype.

At the same time all of the issues recognised during the initial implementation of the teaching method have been solved. This was achieved mostly through a rigorous collection and archiving of any knowledge artefact produced during the course. Naturally this prevented the knowledge and innovation from being lost. On the other hand, from pedagogical point of view, this allowed to closely observe and assess each student individual progress and deploy supplementary teaching tools where needed. These would range from advising on further reading and case study material, through additional tutorial meetings on parametric design and CNC equipment (as in MADA), up to offering individual troubleshooting sessions.

It is important to note that both student groups developed some unique solutions in areas of computer aided design and manufacturing. While it was expected from the WUT students as they have to go through Parametric Design and Advanced CAD Techniques courses before being offered a Digital Fabrication course, it was surprising how well the MADA students performed. Some of these students had no previous experience within the digital paradigm. In fact most of the mentioned unique solutions were developed by the later. This might be related to the fact that course at WUT ended in June 2017 while the one at MADA started in July same year. This means that some of the design, logics and strategies developed by MADA students were based on existing knowledge, thus allowing to creatively reuse the previous designs or research and develop these further. Further analysis offers also an observation that most of the WUT students explored in their work mostly the CAD aspects, while MADA students explored materiality and fabrication processes (CAM) more. This is related to the different environments and actors of the course: distinct teaching curriculums. The WUT students have a strong expertise in digital design including parametric and algorithmic modelling, but suffer from a limited access to CNC tools. Contrary to that, the MADA students operate within a strong tradition of physical model making and have an access to vast fabrication facilities, but lack training in architectural and modelling software. Again this underlines the importance of recognising relationships between entities of a teaching process.

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**CONCLUSIONS**

The designed three-stage process of transferring and creating knowledge based on the increasingly advanced design-research methods proved to offer very good teaching results. This has been confirmed with formal and measurable effects, such as those given by students models as well as process booklets,
which mostly presented high levels of critical observation. The adaptation of the theoretical framework as the teaching method allowed for innovative outcomes to be achieved in several categories. Parametric design and digital workflows, custom CNC methods and fabrication processes are the most visible ones. From the didactic point of view all the above elements allowed to equip students with knowledge and skill-set described in the digital fabrication curriculum. Moreover, operating in design-research context allowed to develop work of an unique character. Work which in many cases significantly outgrown author's expectation: especially in a context of non-digital curriculum of Monash Art Design and Architecture.

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