# Concerning digital design in architectural pedagogy

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**Abstract**. The emerging field of digital design in architecture has changed the way designers think and the way it should be taught. This paper looks at six design educational exercises which have adopted digital tools using various systems. Discussions are rooted in digital design cognition, digital design eco-system and pedagogy. This paper attempts to observe the change of ways of making within these themes using design cognition lens. It is proposed that digital design tool affordances is a pertinent concept to support this emerging field, both pedagogically and with regard to software development. It is also suggested that the digital eco-system framework need to include the dialogue between analogue and digital design tools.
**Keywords:** Digital design cognition, pedagogical approach, design tools affordances

## 1. Introduction

The proliferation of technology in all aspects of human life has also manifested in a digital shift in architecture. For the last fifteen years, the art and methods of digitally oriented materiality, digital morphogenesis and digital fabrication have shaped the way architects think about design. Recent technological developments have moved from mimicking human designers' behaviour and cognition to performing design steps human designers otherwise would not be able to do. In addition, the next generation of architecture students within the next few years is predicted to be able to acquire better understanding of *procedural literacy*, which is "the ability to read and write processes, to engage procedural representation and aesthetics" [1]. *Procedural literacy* is a fundamental skill for designers, and programming is an act of communication and a symbolic way to represent the world, rather than a mere technical task [2]. Architectural pedagogy is also embracing the changes. This paper illustrates six state-of-the-art design practices around the world (at the time this paper was written) and discusses the advances and challenges occurring during this exciting time.

The aims of the paper are to highlight concerns related to the shift in architectural pedagogy and to understand the change in the way of making from the perspective of the design cognition lens. In addition, it highlights the need to embrace changes in architectural pedagogy. The objective is to discuss advances and challenges posited by similar pedagogical exercises. The paper is outlined as follows. Firstly, first and second digital turns will be briefly explained. Secondly, the turns will be contextualised in the architectural pedagogy. Thirdly, the scope of the digital approach in architecture pedagogy in this paper's context will be iterated. Fourthly, the secondary data collection will be explained. Fiftly, discussions will be laid and rooted in: digital design cognition, digital design eco-system and pedagogy. Lastly, conclusions will be drawn.

## 2. First and second digital turns in architecture

The first digital turn in architecture came in the 1990s, when renowned architects embraced digital change from identical copies to customised and non-standardised products. At that time technology was used for mass production [3]. The first generation of digital design and fabrication was born around this time, by suggesting that since digital fabrication does not use mechanical matrixes, casts, stamps or moulds, it does not need to re-use them to minimise cost. In other words, making digital copies will not make the cost cheaper. But in turn, each digitally fabricated item can be different with no extra cost. Carpo highlights that designers and architects were at the spearhead of the *digital mass customisation* ideas, although not all architects are aware of this. Whilst in the first digital turn, we used new machines in conjunction with old science (the way of making); today's digital turn is highlighting the new way of thinking. Today's turn is what Carpo called second digital turn in architecture [3]. We are learning that computers can work better and faster if designers allow them to work following a non-humanistic way (ibid). Separations of the ways architects think, draw and make dissipated. Architects are no longer "agents of notation" who send files to factories, according to Carpo. The iterative cycle of think-draw-make is exhibited as early as design briefs are given. This cycle also presents the act of making as an essential skill to be re-instated in architecture education.

These turns in fact changed the way architecture knowledge is acquired. The call to educate the new generation of digital design specialists, a new taxonomy of digital architecture theory, and challenges in design pedagogy has been posited by Oxman et al. in 2008 [4]. And yet, in nearly a decade, a pedagogical shift still remains a relatively new concept. Oxman and Oxman also edited a book to build the theoretical foundations of this new architecture in 2014 [5]. New epistemology of digital in architecture is fundamentally built around areas such as digitally generated materiality, digital morphogenesis and fabrication in design.

## 3. Architectural pedagogy

The architectural studio culture has been inherited from Ecole des Beaux-Art and its atelier model, instead of having lecture classes as the most common mode of teaching and learning as in other disciplines [6]. The studio pedagogy approach is always complemented by other modules and it is the platform to elaborate knowledge acquired in these modules, by working on integrated design solutions. In the studio setting, architecture students usually develop their design project ideas (within the prescribed duration, usually one academic semester) using various design media. Within this duration, academics and tutors facilitate how ideas are developed. Feedback from tutors and peers is usually obtained after design students present their work, usually happening regularly (once a week, for instance) for the duration of the course. Formal reviews are usually held in the middle of the studio duration with a final crit at the end of study period. The setting is often called 'crit' or 'critique' and it can be done individually or in the form of groups. Architecture studio is a central activity of architectural pedagogy and is also considered the hub of design experiments. This paper presents six design education practices (mostly in design studio settings) which predominantly used digital tools.

## 4. Scope of digital design in architecture in this paper

The recent computational design thinking is an evolution of the previous approach, which was known as computer-aided design thinking. While the computer-aided approach assumes an object-based strategy to encapsulate information into symbolic representations, a computational approach enables specific data to be realised from initial abstraction [7]. In the latter approach, the designer acts as author of rules of implicit descriptions which then are translated into form. The key difference is in what Kostas Terzidis elaborates, it lies between computerisation and computation. Computerisation mimics designing actions and it is a digitisation of processes that are preconceived, predetermined and well defined [8]. Computation, conversely, is a means to explore the indeterminate, vague, unclear and ill-defined processes (ibid).

This paper serves as a starting point to investigate digital design in architecture in relation with the design cognition lens. A bottom-up approach is utilised by collecting examples of design studio exercises which are immersive with the use digital tools. Digital tools in this paper are seen as broad

methods involving the use of computers of some sort. The author positions herself to seek, in various ways, the act of making in these design education exercises without differentiating between the two kinds of processes.

## 5. Research methodology

This paper is presented as a secondary piece of research. Most of the study cases were first encountered by the author during the 23rd CAADRIA (Computer-Aided Architectural Design Research in Asia) 2018 conference in Beijing. In total there are six design education practices in five universities. Although selection of these practices is limited to those which were published, these below-mentioned practices were chosen to represent the state of current architectural pedagogy. Table 1 enumerates the design education practices.

**Table 1.** List of observed design educational practices

| Case studies: | Digital Design Environment | Location |
|---|---|---|
| 1- Dorta et al.[9] | Real time and immersive co-design environment, called Hybrid Ideation Space (HIS): 2D sketching, pseudo-3D sketching, 360° immersive sketches, 3D models, physical models and 4D 360° Immersive Animations. | University of Montreal, Canada |
| 2- Fereos et al.[10] | "Spaceship Architecture" bachelor design studio. Workshops and tutorials on: Rhinoceros 3D, Grasshopper 3D, Phyton and CSharp within Grasshopper, digital fabrication and model making workshops. | University of Innsbruck, Austria |
| 3- Hopfenblatt and Balakrishnan [11] | A multi-platform immersive environment: Unity game engine, zSpace Virtual/Augmented Reality desktop monitor (using a stylus) and HTC Vive head-mounted display and handheld controllers. | University of Missouri, USA |
| 4- Oprean et al.[12] | Site data was collected from 360° images and videos. Immersive environment with three types of headset (Web VR, HTC Vice and cardboard with Android phone). | The Pennsylvania State University, USA |
| 5- Rogers et al.[13] | Quela within Grasshopper, Autodesk ReCap Photo, Hyve 3d, Google Tilt Brush, Rhinoneros3D, Fuzor and Unity. | Victoria University of Wellington, New Zealand |
| 6- Lo and Schnabel[14] | Virtual and Augmented Studio Environment (VASE): HTC Vive headsets, Microsoft Hololens and Hyve3D. | Victoria University of Wellington, New Zealand |

The first case study looks at utilisation of Hybrid Ideation. It is a co-design environment without headsets, which allows immersive projection in a 360° semi-spherical display. The system allows freehand sketching via a pen-tablet device. Students were given options to develop ideas using 2D images, orthographic and perspectival sketching, 3D CAD models, physical models and 360° immersive video. Freehand sketching and verbal exteriorisation were encouraged. HIS was used during an hour of design session every week, the rest of the time students worked in a traditional studio setting. The entirety of different representational media is called the *Representational*

*Ecosystem*. It envisions new paradigm of hybrid approach between: immersive life-size visualisation, freehand sketching and local and remote collaboration. The *Augmented Design Studio* was carried out in collaboration with two partners from industry. The study proposes the paradigm for the new Representational Ecosystem for teaching. They are: technology should be *bilaterally hybrid*, to support *multiple kinds of representations,* to implement *multiple scales including full immersion* and to allow *active and intuitive co-design* [9]. The hybrid way of making in this exercise was multifaceted and included various design tools and social aspects of designing (co-designing experience).

The second case study is called *Spaceship Architecture*; introducing integrated science-fiction scenarios in an architecture design studio. The authors argue that by introducing design topics derived from science fiction, video games, comics and animation, a variety of computational design elements can be unveiled, possibly towards computer oriented technology rather than computationally aided one. The experimental architecture also follows a procedural approach in which the design objective is not predefined. Two distinct parts of the studio were 1) Analysis: digitally modelling, analysing and further refining from a chosen well-known sci-fi example and 2) Synthesis: development of the architectural proposal from the first part's. Workshops and tutorials throughout the year can be found in Table 1. 28 modelling and design computation techniques used in the first and second semesters were mapped, for instance "the use of Nurbs modelling", "Scripting C#", "Laser Cutting" or "Fabrication Optimisation". It was found that in the second semester, approaches were found to be more diversified as a result of students having gained computational knowledge.

The third case study extends the Nine Square Grid design problem, pioneered by John Hedjuk and other influential educators. It is one of the most influential exercises for spatial reasoning based on abstract forms, with open-ended design problem using 3x3 spaces. The Nine Cube VR is a digital tool developed by Hopfenblatt and Balakrisnan and is deployed on two virtual reality displays [11]. It is a digital tool intended for early studio education. The first display is zSpace, which is an interactive desktop monitor with stylus and a headset (HTC Vive). The second display is 1:1 scale display using the HTC Vive VR display, allowing students to have spatial experience, which is then subsequently used to inform the physical models. This system allows designers to create compositions in the immersed environment, including an interactive light experiment and changeable colours. In addition, the application allows design alternatives to be produced intuitively and rapidly.

The fourth case study explores immersive experiences of a remote site in Rio, Brazil. Oprean et al. hypothesise that immersive environment can enhance understanding of a site [12]. In addition, site information can be obtained remotely and it is particularly helpful when a site visit is not possible. The scope of the study focuses on developing a workflow with three different immersive experiences applications. Apart from a potential alternative to a site visit, it was found that the immersive applications aided dialogue with the community members when solutions were presented. It also improves understanding of physical features compared to traditional media. The preliminary results concerning potential immersive environment to supplement site experiences were found to be positive. Sense of presence occurred in all applications, and interaction with site community members was able to be achieved. However, according to the authors, there is a lack of detailed information and the inability to convey the social dimension of the community.

The fifth case study proposes a new methodological ecosystem transitioning away from traditional design methodology. The key to success is the interconnectivity between multiple design tools in a generative way, and it was tested in a studio-case study. These design tools were the parameters of the case study and were individually observed in terms of interconnectivity: agent simulations, artistic image processing analysis, site photogrammetry, 3D immersive sketching both abstract and to site-scale, parametric design generation and virtual reality style presentations [13]. It was observed that each selected design tool has its advantages and disadvantages with regards to the designers and the tools themselves. The case study embraces the *digital culture* where designers are immersed and revolve around multiple design technologies in generative ways. In addition, the *Interconnective Design Methodology Ecosystem* framework posits digital tools as an ecosystem of interaction.

The sixth case study (from the same university as the fifth case study) discusses benefits and challenges on adopting virtual reality equipment with various design software. In addition, it looks at how the exchange between tutors and students can be enhanced in a design studio setting. A dynamic eco-system of the design process was expanded from the conventional design process, including intricate connections between multiple design software. Design related functions are elaborated such as: design, documentation, exploration and visualisation. Relations to other functions related to design are drawn, such as: coding, narrating, gamifying and experiencing. Similarly with the fifth case study, interoperability is the key in terms of interaction between software. It was observed that virtual reality eco-system exists and it is advisable to explore full potential of virtual reality technology with regards to architectural design. It is observed that the eco-system allows design movement in multi-dimensional experiences and narratives, which also allow immersive social interaction.

## 6. Discussion

The way of making and exploring design with digital tools as illustrated in the case studies above provide distinct learning experiences depending on the design apparatuses design students utilise, in comparison with analogue design tools. For instance, the multifaceted experience in case study #1, the *Hybrid Design Ideation* allows learning to be fleeting between the physical and virtual worlds. Case study #4 collects site data in various format such as 360° videos, footage and images; which then can be viewed in an immersive environment. The act of making is shifted from externalising ideas through drawings to creating an environment whereby designers themselves can simulate ideas on a 1:1 scale and also modify in real time. Making processes become highly driven by the designer as the "conductor", taking charge of the "orchestra" of good fit selection between tools, design process and the intended design. The case studies also highlight the fundamental notion of interactions between the design tools as an ecosystem.

It is apparent that digital design tools provide significant support to the design process and pedagogical advancement. Mainly, digital tools allow designers to manipulate and simulate ideas in ways that analogue design tools such as pen and paper or physical model making struggle to do within the same timeframe, such as real-time simulation and manipulation at multiple scales, open-ended digital explorations, a remote studio site experience and real-time design knowledge exchange between tutors and students and with clients. Although it was noted that specialist software skill is a prerequisite, which in turn can be a hindrance to explore full potential of design software or possibly lead to design fixation; it is generally accepted that such technological development offers substantial assistance to the design process. Discussion below is presented around three main ideas: 1) digital design cognition, 2) the digital design ecosystem and 3) how to facilitate pedagogical transitions. These ideas encapsulate the imminent concerns about this new architecture.

### *6.1. Digital design cognition*

Firstly, digital design cognition is discussed. As a result of the new way of thinking about architecture and shift of paradigm, the current design cognition studies have to accommodate these changes also. Major changes are entailed from the way we study designers, the "designerly way of knowing" as Cross elaborated [15]. What is prominent in this shift is the relational value between designers and digital tools. (Analogue) design cognition studies such issues as ways designers utilise pen and paper or how physical model making traditionally focused the exploration in the designer's mind. The digital design cognition taxonomy may possibly be more suitable to view using the *embodied cognition lens*. This research program challenges the long known cognitive science; by suggesting that cognitive processes are deeply rooted in the body's interaction with the world [16-18]. In other words, designing can be perceived as an embodied experience [19], a dialogue which is distributed across mind, body and design environment. Instead of asking "how do designers design"; the new question could be "What is the dialogue between designers and (digital) design tools in the ideation process?" By using the *embodied cognition lens*, designers and design tools are regarded as equally pertinent and they

both casually affect design results. Relational value between designers and the digital tools can be established and characterised.

Moreover, digital design cognition perhaps needs to be distinguished between computer-aided design cognition and computational design cognition. As mentioned previously, on one hand the two approaches share similarities in terms of the use of technology; on the other hand they possess significant differences in terms of the nature of how technology is used. In the latter approach, technology and design tools serve as vehicles for exploration which are highly related to taking advantage of computer power. Within the six presented case studies, most present the first approach, with the exception of case studies #2 and #5. In addition, Fereos et al. in case study #2 highlights the pertinent concern of how design computation can be taught in a methodological-centric way rather than viewing the approach as a catalogue of software tools. With the adapted *embodied cognition lens* in design studies, possibly these distinctive cognitive actions between the two approaches can be revealed. In previous studies, this author developed a trifold scheme whereby cognitive, bodily and design environmental related processes were mapped and interactions between them were drawn [20]. Computer-aided and computational design cognition perhaps can also be mapped three or perhaps more ways so that interactions can be visualised and differentiated.

From Table 1, a variety of software can be used. In case study #2 and #5 for instance a range of software was used. With the plethora of design tool choices, designers need to acquire specialist software skills. *Affordances,* coined by Gibson [21], are what the environment offers to animals (or an organism). It is a crucial concept in *embodied cognition*, and is often illustrated with the example of the tool. Once it is used, a tool is treated as functional extension of user's body. *Design tool affordances* can be understood as what a design tool provides to designer. For example, VR headsets offer the ability to simulate ideas or to do a walkthrough. Understanding the design tool affordances of each design tool is crucial to build a vocabulary of design thinking with the medium of the tools.

Traditionally, investigating how designers behave in the conceptual design phase when flying ideas are fleeting aims to develop various pedagogical concepts, strategies and tools including better understanding of the world of design and thoughts, and also to improve design processes and products. With the aforementioned changes in the digital world, possibly the aim to study designers behaviour could be translated to increasing understanding of *digital design tools affordances* and to mediate selection of design tools to enhance the design process and its pedagogical support. Digital tools do not work in isolation. In case study #4 for instance, 360° images and 360° videos we collected and used to develop the immersive virtual reality before workflow was observed in three different sets of VR headsets. In case study #1, hybrid analogue and digital tools were used in both real and virtual reality. It was observed that sketches were used until the end of the studio, in combination with pseudo 3D sketches (2D sketches on 3D view, a more economical way to sketch). This leads to consideration of the digital design eco-system.

### *6.2. Digital design eco-system*

Secondly, the digital eco-system hosts a variety of design software in application. In case study #6, an array of design software and its interconnectivity related to their design functions, expanded from conventional design process was elaborated [14]. The functions are design, documentation, exploration and visualisation. Expanded functions from the conventional design process are coding, narrating, gamifying and experiencing. Each software can have multiple functions, and the key factor which links the proposed eco-system is design creativity. In addition to interactivity between design software, case study #1 highlights that bilateral hybrid between analogue and digital environment allow full engagement in the design process to be achieved. In case study #2, in the second semester, students were found to have embraced more diverse techniques during the first semester through the autonomous approach (working on intangible themes). It is noted that in case study #2, 90% of the students had prior knowledge of the use of associative modelling or visual programming. Designers tend to start with software which is familiar to them, the more time they spent on the project, the more diverse techniques were deployed. Case study #6 is in accordance with the idea that designers start

with a familiar technique or software [14]. They also argue that with the vast development of tools, creative flow is moving away from the linear process (exploration→design→visualisation→documentation).

In case study #5, it was argued that the selection of each design tool is an essential ingredient within the ecosystem [13]. They also argue that the constant move from physical and virtual technique is the essence of this eco-system. Each selection entails strengths and weaknesses regarding capabilities of both: the designer and the tool. If we view this in with *embodied cognition lens*, *digital design tool affordances* are crucial components to this system. In contrast to analogue design tools such as pen-and-paper sketches, what design tools can provide to designer work has bidirectional terms. *Effectivities* (ways of acting to realise specific affordances) of designers affect the way tools are used. It also involves a certain degree of familiarisation with the tools.

Interoperability is an important element in this eco-system. Case study #4 reported that problematic content integration and incompatibility with other design tools, the need for special expertise and the high cost of traditional immersive environments are addressed in modern immersive environments. However, problems might arise within the eco-system if designers are not willing to go beyond their familiar software. Being reluctant to learn or limited proficiency with a new technique might lead to design fixation. It is "a blind adherence to a set of ideas or concepts limiting the output of conceptual design" [22]. As a result, design outcome may be compromised.

The expanded eco-system of digital design as proposed by Lo and Schnabel in case study #6 has to be extended more by incorporating analogue design tools, to be able to be a full scale immersive design experience [14].

### *6.3. Pedagogy*

The third factor is the architectural pedagogy. We have seen different pedagogical approaches in the listed case studies with regards to the digital architecture. Case study #1 for instance looks at co-design as a teaching strategy. Case study #2 suggests that working with an intangible theme (spaceship) resulted in an extensive vocabulary of computational means. Case study #3 reintroduced the Nine Grid Problems in a virtual reality environment, which offered valuable meaning to explore spatial presence with an intuitive interface. Case study #4 explored a remote site visit through the use of an immersive environment. Case study #5 and #6 highlight the integration and interaction of multiple design tools, creating the eco-system. In particular, case study #6 illustrates real time social virtual reality as pedagogical approach to boost efficiency in design communication and design understanding for designers.

One of the main concerns related to pedagogical approaches is the way new technology can be understood to be able to influence design thinking. Specialist software requires specialist knowledge, and designers now are exposed to a wide range of design techniques, i.e. the eco-system discussed in the previous section including exemplar techniques listed in Table 1. The challenge could be overwhelming for students who do not have prior experience. One possible first step to reduce the gap between technology and designers is by conducting introductory workshops or kick-off workshops. Aish and Hanna tested three parametric design systems for their suitability for undergraduate teaching [23]. They tested a set of standard modelling exercises in a parametric system (such as "creating of a 2D array of points") with a set of criteria inspired by 'cognitive dimensions' to investigate important conceptual and usability concepts. Subsequently cognitive barriers were inferred, aiming to select the most suitable system for teaching parametric design. With the number of increasing platforms within the mentioned eco-system, possibly every single digital architecture platform needs to be analysed the same way so that characterisations of design tools can suggest appropriate pedagogical support and software design.

Digital skills are paramount to the creation of digital architecture and to avoid early design fixation. Burry illustrates the new approach of *scripting cultures* and highlights that scripting as part of architectural education might be deemed to be necessary but also to avoid over concern to teach coding skills so that we do not repeat the errors of the 1990s when CAD equals to drafting [24]. Case

study #2 used kick off workshops and lectures throughout the year and emphasises the importance of building each phase of the studio on the core idea of transferable knowledge to the next phase [10]. A pedagogic environment which allows designers to communicate their ideas with confidence is crucial for the design process. If designers are hindered by the software, a fruitful learning process will also be compromised. In study case #3, authors suggest that pedagogical tools should facilitate developing skills to shape human experience through interactive exploration [11]. In Nine Cube VR, simulations of human experience can be explored at a real-world scale.

Case study #6 reports on how virtual reality changes design exchange between tutors and students, and in case study #1 it was suggested that the educator has to also design with the student in order to teach him/her to design. With the rapid feedback cycle, for instance using immersive space sketching, knowledge transfer between design students and tutors is enhanced. To bring out the full potential of digital design tools, it is suggested that understanding of the digital design eco-system must be ameliorated. Prior experience of computer programming perhaps is important, to be point where basic knowledge is acquired. This can be achieved possibly through some elective modules or foundation courses. To build students' confidence when using technology and to avoid early design fixation, students need to have an understanding of each *design tool affordance* and build a unique digital design eco-system which suit their individual digital skills.

## 7. Conclusions and future work

We have established that the ongoing digital turn has led to major changes in different aspects of designing and the way it should be taught. Whereas previously architects usually engaged in a sending "files-to-factory" process, the shift is now to where architecture practices are at the centre of act of: notating, representing and fabricating. It highlights challenges in terms of how architectural education addresses these changes. Through observations of six design education practices presented in recent publications, general concerns related to architectural pedagogy have been illustrated. Without empirical observations, generalisations of finding of this paper are limited, however it highlights important notions related to digital design cognition, the eco-system and pedagogical concerns. These three notions are connected in ways that understanding of each concern might lead to better pedagogical support.

Transitions from the use of merely analogue design tools can possibly be facilitated by: reducing the gap between technology and designers, giving kick-off workshops and lectures, pedagogical tools for facilitating human experience, educators to co-design with students, introducing algorithmic thinking, drawing attention to differences between computer-aided or computational design approaches and lastly understanding the *digital design ecosystem* and *design tool affordances.*

With regards to design cognition, digital design cognition as the frontier to study the way designers behave during the ideation process should include *digital design tools affordances* within the eco-system. Digital design eco-system which encapsulates not only relationships between design technique but also relations between analogue and digital design tools should be considered, if we are to take full advantage of the digital in architecture. In terms of pedagogy, whilst it is reported that digital design enhances dialogue between students and tutors; it is also noted that prerequisite digital skills are pertinent and perhaps can be addressed in foundation courses or pre-university education. Future work in the line of demystifying *digital tools affordances* is considered, as has been initiated [23], to be beneficial for pedagogical support and software design.

The shift in the act of think-draw-make celebrates craftsmanship, while at the same time understanding and knowing when and why digital mass customisation is needed should be crucially addressed in architecture pedagogy. At the same time architecture students should also be made aware of how to take full advantage of computer power, to be able to understand the full potential of digital design in architecture. The new way of making changes the relational value of designers and digital design tools in comparison to analogue design tools.

**References**


[1] Mateas M 2005 Procedural literacy: educating the new media practitioner. On the Horizon 13 101-11

[2] Reas C, McWilliams C 2011 Form+ Code: in design, art, and architecture: Princeton Architecturel Press)

[3] Carpo M 2017 The Second Digital Turn: Design Beyond Intelligence: MIT Press)

[4] Oxman R 2008 Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium. Design Studies 29 99-120

[5] Oxman R, Oxman R 2014 Theories of the digital in architecture / [edited by] Rivka Oxman and Robert Oxman: Routledge, Taylor & Francis Group

[6] Oh Y, Ishizaki S, Gross MD, Yi-Luen Do E 2013 A theoretical framework of design critiquing in architecture studios. Design Studies 34 302-25

[7] Ahlquist S, Menges A 2011 Introduction: Computational Design Thinking Computational Design Thinking ed editor Chichester: Chichester : John Wiley pp. 10-29

[8] Terzidis K 2011 Algorithmic Form Computational Design Thinking ed editor Chichester: Chichester : John Wiley pp. 94-101

[9] Dorta T, Kinayoglu G, Boudhraâ S 2016 A new representational ecosystem for design teaching in the studio. Design Studies 47 164-86

[10] Fereos P, Tsiliakos M, Jaschke C 2018 Spaceship Architecture Learning, Adapting and Prototyping Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018 pp. 81-90

[11] Hopfenblatt J, Balakrishnan B 2018 The "Nine-square Grid" revisited: 9-Cube VR- An Exploratory Virtual Reality Instruction Tool for Foundation Studios Learning, Adapting and Prototyping Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018 pp. 463-71

[12] Oprean D, Verniz D, Zhao J, Wallgrun JO, Duarte JP, Klippel A 2018 Remote Studio Site Experiences: Investigating the Potential to Develop the Immersive Site Visit Learning, Adapting and Prototyping Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018 pp. 422-30

[13] Rogers J, Schnabel MA, Lo TT 2018 Digital Culture Learning, Adapting and Prototyping Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018 pp. 493-502

[14] Lo TT, Schnabel MA 2018 Virtual & Augmented Studio Environment (VASE) Learning, Adapting and Prototyping Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2018 pp. 443-52

[15] Cross N 2006 Designerly ways of knowing : with 15 figures / Nigel Cross: Springer

[16] Wilson M 2008 19 - How Did We Get from There to Here? An Evolutionary Perspective on Embodied Cognition Handbook of Cognitive Science) ed editor (San Diego: Elsevier) 373-93

[17] Shapiro L 2011 Embodied cognition: Routledge

[18] Clark A, Chalmers DJ 1998 The extended mind. Analysis 58 7-19

[19] Tedjosaputro MA, Shih Y-T 2019 Perceiving Design Processes as Embodied Experience Research into Design for a Connected World ed editor: Springer pp. 21-31

[20] Tedjosaputro MA, Shih Y-T 2018 A visualization tool to investigate the interplay of external and internal processes International Conference on-Design Computing and Cognition: Springer pp. 669-86

[21] Gibson JJ 1986 The ecological approach to visual perception / James J. Gibson: Lawrence Erlbaum Associates

[22] Jansson DG, Smith SM 1991 Design fixation. Design Studies 12 3-11

[23] Aish R, Hanna S 2017 Comparative evaluation of parametric design systems for teaching design computation. Design Studies 52 144-72

[24] Burry M 2011 Scripting cultures: Architectural design and programming: John Wiley & Sons