Modular, Flexible, Customizable Housing and 3D Printed

An experiment in architectural education

José Beirão¹, Nuno Mateus², João Siopa Alves³
¹,²,³Faculdade de Arquitetura, Universidade de Lisboa
¹jnb@fa.ulisboa.pt ²nunomateus@arx.pt ³joaopedrosiopaalves@gmail.com

Technological developments in construction always bring new expectations in terms of design possibilities. The use of digital tools both in design exploration and applied to explore new forms of computer controlled manufacture provide opportunities for the emergence of new tectonics. Because these transformations change our construction reality fast and with impacts never seen before, it is important that architectural education follows such change and prepares students for what will be their future really, making them capable to accept and incorporate the tectonic implications of digital tools and construction methods in the way they design. This paper shows a tutored approach to mass customized housing resorting to 3D printed parametric modular construction. Please write your abstract here by clicking this paragraph.

Keywords: caad education, mass customization, 3D printed housing

INTRODUCTION
Advances in technology have produced new expectations in terms of design possibilities. The total implications in the field of architectural tectonics are yet to be understood in a comprehensive way (Kolarevic 2004). However, the housing market has already incorporated some of the peculiarities of digital technologies in their demands forcing architects to respond to architectural problems in a very different way than traditionally used to offer. Housing in particular is very much affected, qualitatively speaking, by the requests for fast, large scale housing developments. Typically, the market requests fast responses and puts all responsibilities on the architects. The market wants, more, better, cheaper and more responsibility.

On the opposite side, contemporary culture has developed a strong taste for individuality which tends to bring to the market demands regarding design customization at various levels and scales of design production, where architecture, essentially due to a scale that induces resilience, tends to adapt in a slower manner. The gigantic changes in China’s cities have shown clearly that the architectural housing market is still guided by the mass production paradigm and is far from convincing investors that difference and personalization are technologically available commodities.

Regardless of this reality, architectural education seems to maintain mostly traditional curricula without truly questioning the implications of this status quo in the education curricula. It is not just a ques-
tion of including contents where CAD or BIM tools are taught, but to acknowledge that the new reality implies design questions and approaches that might not be addressed without resorting to new technological methods. Methods are indeed the key issues, not the tools. This implies clearly adequate pedagogic strategy.

Facts in present architectural reality tell us that radical changes are close to occur. Let us point some:

1. Architectural production is becoming more and more digital, the present paradigm being the production of digitally informed architectural integrated models by resorting to BIM software.

2. Rule based design, whether more parametric or more recursive allow the exploration of design variations in a scale never seen before. Such types of exploration allow for two possible attitudes in a design process: (1) augmenting the scope of design exploration towards an extreme extent (a strive for excellence based on raising the degree of experimentation and trial) (Kolarevic 2004); and (2) the exploration of systems of design objects, by resorting to rule based design languages and therefore producing sets of object variations within some predefined spatial and/or formal type where a specific instantiation may be the subject of some form of customization or adaptation to specific needs (Duarte 2005).

3. Society demands more and more the production of originality, diversity, customizable solutions, cheaper solutions, but faster, more efficiently and tailored to the users' idiosyncrasies (Ratti 2015).

4. Digital fabrication raised astronomically the expectations regarding architectural production. Still far from a totally digital production, the idea that we may produce architecture from sketch to construction in a continuously digital flow has entered the expectations of the market. Some facts can be highlighted in this context: (a) architectural elements (if not the whole house) can be 3D printed [1], [2], [3]; (b) a parametric (or generative) model may produce a diversity of objects that although different can be printed with similar effort - i.e., a project, or parts composing a project, can be different and printed with similar effort; (c) materials technology develops further and further more materials tailored to design specifications that may be used in digital prints allowing to print houses or parts of houses with materials technically prescribed for a specific performance whether such performance is simply aesthetical or defined in terms of physical behavior (Jancic 2016), (Oxman, 2010), (Van Wijk and Van Wijk 2015).

These facts support the argument that construction tectonics will change, and these changes will also change drastically our way of designing houses. It is the responsibility of architectural schools to address this new reality and prepare students for it. The underlying assumption is that such reality requires new teaching methods and new approaches to architectural education.

This paper departs from this assumption and reports the results of a final architecture master project where the design problem was set based on a few technological assumptions to architecturally explore their tectonic implications.

FRAMEWORK
Before detailing it is important to explain the framework upon which the Final Master Architecture Project is developed at the Faculty of Architecture at the University of Lisbon. The program starts at the first semester of the fifth year of studies (9th semester) where a large study area is given to all the students. The urban scale approach and analysis is developed during this semester and involves collaborative work. This stage allows the students to collect detailed information on their study areas developing a deep knowledge of its problems and morphological characteristics. After this semester, and after attending a course on research methodology, the stu-
students develop their Master Project proposal which at this stage is simply a short summary of goals drawn upon an architectural problem that was identified during the analytical work. From this point onwards, their work is supervised following a tutorial principle, and the students become totally responsible for the direction their work takes together with the guidance from their supervisors. The master student is therefore guided towards framing his/her own design problem.

In the case exposed in this paper, the student started by presenting his will to explore the use of digital fabrication in architectural design. This generic intention became a specific program involving research and design which had as generic intention the exploration of digital tectonics in housing architecture.

**METHODOLOGY**

Once the generic intention of exploring digital tectonics in housing architecture was defined, and leaning on his supervisors’ advice, the student further detailed the scope of his work. The role of supervision at this point was to set together with the student a consistent methodology that could outline and support his work from the research contents to the design tasks.

The applied methodology set together with the student followed a sequence of stages:

1. Literature review and survey on the uses of digital fabrication in architecture practice with a strong focus on the use of 3D printing. The main goal at this stage was the identification of the present state of 3D printing in construction and envisioned potentials found in the literature.

2. Literature review and survey on architectural practice with the purpose of identifying the advances and state of the art on the use of prototyping techniques as methods to support architectural ideation and design at the office, more specifically regarding the use of 3D printing during the design process.

3. After the survey, a research question was formulated: what are the impacts of 3D printing in the production of housing architectural designs? What are the new tectonics of housing design within the reality of 3D printing? What will be a new architectural expression based on the possibilities of digital fabrication?

4. From these questions, the student defined a set of assumptions to guide a housing design proposal: (a) The design result should be a system able to produce several house types providing product customization; (b) The design process should resort as much as possible to digital tools and techniques trying to explore design potentials that otherwise would not be possible; (c) The design should explore the tectonics of a new hypothetical material considering that this material congregates a set of properties based on state of the art already existent construction realities; these were: concrete based material, coloured, structurally resistant, amenable for printing resorting to a CNC extrusion head; (d) The geometrical limitations of the printed parts should result from the constraints of a hypothetical (but plausible) printer size; (e) The printed parts should be building components, modular but parametrically adjustable to shape variations in the lot; (f) Material appearance should be that resulting from the material and printing technique.

5. Design process resorting to digital techniques including digital prototyping techniques such as FDM printing, CNC milling and laser cutting. In this case, the chosen techniques were those available at the Faculty of Architecture and essentially an FDM printer built by the student himself.

**PRE-REQUISITES**

This work would not have been possible if the student had not been able to acquire some preliminary knowledge and experience, namely on parametric
modelling and on 3D printing. For this he learned 3D modelling using Rhinoceros and parametric modelling using Grasshopper following a course on parametric modelling at the Faculty of Architecture. He also had an internship at DUS Architects in Amsterdam where he was able to follow their seminal project: the 3D Printed Canal House [1], where he became acquainted with the complexity of real scale architectural 3D printing, but also provided him the knowledge on how to address many of the technical construction issues involved in this type of construction technique, namely, structural problems, wall design, embedded infrastructure and material issues.

After this experience, the student participated in a workshop on cork design developed at the Faculty of Architecture at the University of Lisbon [4] where he tried to develop a printable material using cork dust (see figure 1). Figures 1 and 2 show partial results of these experimentation process. the student developed several adaptations in his own printer to experiment several options regarding material mixture and extrusion nozzle diameter (see figure 2). Even though this part of the work was not totally successful, this experience prepared the student for difficulties and issues already posed by Jancic (2016) in his research on additive manufacture digital techniques. This workshop had the format of a one-month intensive summer workshop.

GOAL

The main goal was to design a parametric modular housing system exploring the tectonics of a new material. The underlying ambition was to prove that the
digital methods can support the production of architectural excellence and new forms of expression. At the root of this work lies an important assumption: a hypothetical material. However, the hypothetical material at the basis of this work is not conjectural. It is based on partial realities that the technology has already accomplished that evidence not just the desire to produce such a material but also on the fact that many researchers are working on the development of such materials. Examples considered in this work were: the 3D printed canal house by DUS architects [1], the WINSUN 3D printed construction [2] and the WASP Project [3] among others that will not be mentioned in this paper. The students studied in detail the work developed by these projects and wrote a state of the art summary synthesizing the present achievements in the fields of digital additive construction. Details may be consulted in the dissertation (Alves 2017).

Having done an extensive survey on state of the art digital architectural manufacture, the student came down to a synthesis on the characteristics of the material he was expecting to use. These characteristics were:

- The material is a printable concrete including some form of dust or small grained granulated natural and recyclable material. These characteristics result both from the student’s contact with DUS Architects who research for a similar and from his own experiences with cork during the cork workshop.
- The material is printable by layering material through an extrusion nozzle the same way Wimsun systems produce their concrete houses, but assuming the future technology will admit a much higher definition, capable of printing decorative low relief motives (see figure 3 - print tests performed by the student).
- That the material would have a light colour like the concrete used by Carrilho da Graça in the Lisbon Cruiser Terminal. The concrete used in this building is already a low weight concrete containing granulated cork.
- The printed modules would be a self-supporting system bearing the maximum weight of three levels. The wall prints would be hollow for lowering the total construction weight following a three dimensional cell system inspired by the 3D Printed Canal House Figure 3
Test prints of decorative motives inspired by traditional Portuguese ceramic tiles. On the left, a 1/1 scale model in concrete; on the right a set of scale 1/50 construction modules printed with alternative decorative motives.
but adapted to the expected nozzle diameter (see figure 4).

- The printing process would use a transportable printer that could be delivered to the construction site with a single truck hence limiting the size of the printed modules (see figure 5).

DESIGN PROCESS
The most important detail to point regarding the design process is that the student was enticed to explore the possibilities of the technique at all levels of detail and scale, exploring not just spatial and structural concepts but also the parametric modularity of the system, the potential to include several forms of bas-relief motives and the exploration of texture. Furthermore, in addition to the production of original housing and architectural language, the student explored also the adaption of the system in architectural rehabilitation. The design was developed from urban scale to construction detailing. It is essential to refer that even though the technical design brief defined a 3D printable modular housing system amenable for the production of housing customization, supervision kept the focus always on tectonic and architectural expression exploring both spatial qualities, natural light and material expression (see figure 6). Design consistency was a must throughout the process.

The student was also encouraged to resort as much as possible to the use of digital techniques in his design process, from testing models using FDM prints to the exploration of a virtual model by resorting to virtual reality using software “Kubity” with VR Shinecon V2 Oculus.

The most interesting aspect of the project chal-
Figure 6
Modular system showing printed parts. Because parts result from 3D printing each part can be customized embedding customized bas-relief or slight geometrical adaptations to fit site irregularities.

...The challenge was the fact that 3D printing allowed for a flexible interpretation of what a module in an architectural system is. The fact that the design system is parametric allows for a modular system to adapt to geometry changes in site implantation even though the type under application might be exactly the same; only the sizes change to adapt to site because modules allow parametric variation within certain limits. Then, because fabrication is digital, module manufacture does not depend on exact dimensions and therefore each module can be printed with slightly similar but not necessarily equal parameters (see figure 7 and figure 8). The traditional conception of a modular system is hence questioned and simultaneously extended. Slight differences in modules do not affect the modular concept nor costs or other technical difficulties. On the contrary, the advantages of modular construction can therefore be extended to situations involving slight geometrical adaptations and shape twists that would not be possible in traditional modular systems. Plus, modules can be customized even with 3D printed alternative...
finishes, all coming from the architect’s conception but also amenable for customization, in which a final user or customer might choose a preferred finish from a parametric board of options.

Finally, the student explored all constructive possibilities of the system including how the construction system would solve infrastructure, technical installations and other architectural elements that could have an architectural expression based on the digital construction characteristics (see figure 9).

CONCLUSION
The master final project presented in this paper shows the results of a pedagogical approach to future ways of producing housing. The obtained results show that the approach equips the student with skills that enable the young architect to respond to the new requests of the architectural market, in particular, the fast and efficient production (from design to construction) of diversity and customization adaptable to different housing types, geometry and spatial requisites. This program prepares the young architectural professional to find tectonic expression in a digital world, create, develop, explore and build using digital media and prepares him/her to the challenges of a digital future under continuous transformation.

The results of this work strongly differ from studio based work involving a common program distributed to several students, and can only be developed in contexts like the Final Master Project program as is ran at the Faculty of architecture at University of Lisbon, which is based on individual tutorial teaching. The development of specific topics of research and design methods become therefore a program built between student and tutors, but on the other hand any positive result can become a teaching experience to replicate or even apply on traditional studio environment. In fact, the final architec-
ture project at this University used to have such format in the past and some pioneering applications of this type of program had already been applied between 2001 and 2007 (Duarte and Beirão 2011).

ACKNOWLEDGEMENTS
Even though this paper’s focus resides on the pedagogical strategy it would not have been possible without the endeavor of João Siopa Alves who developed the design and is the author of all the images presented in the paper. His contribution extends to the paper contents. As might be understood in the paper, the pedagogical strategy was built over team work and highly depends on student endeavor. Supervision is only possible through bidirectional communication and effort. João got the best mark given at the Faculty and a Honorable Mention at the Archiprix Prize, Portugal. The other authors share the responsibility of the pedagogical program.

REFERENCES
Alves, JS 2017, A CASA METAMÓRFICA Habitação modular, flexível, personalizável e impressa, Master’s Thesis, Faculdade de Arquitetura, Universidade de Lisboa
Jancic, L 2016, Implications of the Use of Additive Manufacturing in Architectural Design., Ph.D. Thesis, Faculty of Architecture, University of Ljubljana
KOLAREVIC, B 2004, Architecture in the Digital Age: Design and Manufacturing, Taylor & Francis
LEACH, N, Turnbull, D and Williams, CJK (eds) 2004, Digital Tectonics, Wiley
Ratti, C 2015, Open Source Architecture, Thames & Hudson, London

VAN WIJK, A and VAN WIJK, I 2015, 3D Printing with Biomaterials: Towards a Sustainable and Circular Economy, IOS Press, Delft