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From research to practice: exploring 3D printing in production of architectural Mashrabiya

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Abstract: Digital fabrication has suggested the supplanting of labour via robotics since it affords substantial increases in speed and accuracy in the development of architectural components. This potentiality might offer solutions for architectures on the verge of extinction due to vanishing skilled labour. This research investigates the possibilities of using new manufacturing techniques to replace the historic artisans with digital master craftsmen, specifically re-developing the Mashrabiya. The work looks at several case studies in architecture and 3D printing; bridging the gap between historically relevant climactic design strategies and digital or parametric design and fabrication. This paper concludes with a summary of a parametrically developed Mashrabiya screen system developed by the authors that is programmable based on core criteria found in the archetype and is currently being explored for product development. The work contributes to the developing body of knowledge surrounding the applications and implications of technologies that enable mass customization.

Keywords: Mashrabiya; architecture; 3D printing; façade; parametric design.

1. Introduction

> “Architecture needs mechanisms that allow it to become connected to culture. It achieves this by continually capturing the forces that shape society as material to work with it. Architecture’s materiality is therefore a composite one, made up of visible as well as invisible forces.” Moussavi (2008).

Contemporary 3D printing is currently disputing the boundaries of construction and manufacturing which were previously confined within traditional making techniques. As a result, this is generating a gap between digital intentions and physical media (Choma, 2010). Choma (2010) appropriately asked the question: “How do we qualify the necessities of fabrication processes in the current discourse?” Market demands and the changes in social lifestyle have demanded innovation of traditional products to suit today’s needs. In the Middle East, since the early ages of the Islamic religion, the harsh environment and the social variables have shaped design, architecture and product manufacturing (Fathy, 1986). The complexity of such culture is seen in the production of Mashrabiya, an element that operates within social, architectural, cultural and environmental infrastructures. This traditionally hand crafted architecture is an “endangered species” as a result of the loss of the required craftsmen in its construction.

Formally, the Mashrabiya is a wood lattice screen, that is then manufactured by crafting and assembling an array of small wooden parts that are then fitted together to form the overall assembly. Historically, this system has maintained five architectural functions through parametric variation of its members: passage of light, control of airflow, temperature of air current and humidity, and the privacy of the woman’s quarter (Harim) in courtyard houses in the Middle East (Fathy, 1986). The small wooden parts are made in a variety of ways, however, more commonly, they are turned on a lathe by hand or machine.

Within digital fabrication, technology has begun to suggest the supplanting of labor via robotics since it potentially affords substantial increases in speed and accuracy in the development of architectural components and assemblies while also maintaining specifically programmed dimensions of craft (Dritsas and Yeo, 2013). If form does in fact follow parameters through specifically articulated protocols (Anderson and Tang, 2011) then perhaps the appropriate answer to Choma’s question is in the translating and subsequent reprogramming of culturally relevant architecture constructs through proper design and manufacturing.

This work is an investigation into the possibilities of using new manufacturing techniques that replace the historic masters with digital craftsmen and a 3D printer of large scale objects such as Mashrabiya screens is discussed and tested here. The work looks at several case studies in Architecture and 3D printing; bridging the gap between the digital intentions and physical media while simultaneously engaging demand, function and manufacturing. This research contributes to the understanding and implications of technologies that enable mass customization. The designed screen product hints to its economic model, as well as an inventory of prices and materials of large scale printers. This will be significant in predicting the future benefits and obstacles of 3D printed large scale architecture products in the coming 5 - 10 years. This research represents the second phase of a three year research project, looking into these manufacturing processes and parametric programming of the cultural and functional conditions. The role of the new protocols in current practice is the core of this research.

2. Manufacturing architecture in the age of the 3rd industrial revolution

2.1. 3D printed architecture products

Rapid Prototyping or 3D Printing is an additive CAM process through which various materials are layered through various machining processes. The materials utilized typically are intended for a short life expectancy and are non-performing structurally; they are meant for immediate analysis and evaluation of form, scale, fit, etc. (Rael and Fratello, 2011). Exceptions to this are emerging as the parametric modeling and digital optimization become more integrated into the design process. Crolla and Williams (2014) *Smart Nodes*, is a strong example of how the technologies are enabling new modes of production and assembly in Architecture. As noted by Crolla and Williams, this technology is not necessarily “new” but as its patents have begun to expire the machines and the materials have become prolific and omnipresent. It can be hypothesized that the cost of this technology could potentially be reduced to the extent that additive manufacturing could be competitive with traditional manufacturing (Crolla and Williams, 2014).

Winsun Decoration Design Engineering Co. already advertises the 3D printing of homes as a 'Product' (yhbm.com, 2015) (Figure 1) and Brian Peters (2013) has developed 3D printers capable of 3D printing customized bricks that are parametrically optimized around structural and ornamental performance.

Figure 1: Winsun Decoration Design Engineering Co. Concrete 3D printing homes technology (http://www.yhbm.com/index.php?m=content&c=index&a=lists&catid=67).

While questions arise in light of this revolution as notions of authorship become relevant and the cultural implications of potentially supplanting construction labor loom in the future, this technology has great potential to save historic architectural paradigms and construction types (Dritsas and Yeo, 2013). Given that, according to WinSun, the Egyptian government recently put in a 20,000 unit order with Winsun, the revolution is upon us. The potential for the exploration of 3D printing being informed by parametric systems guided by culture and environmental issues exists, but simultaneously the risk of generating an expansive Pruitt-Igoe that might not able to be killed with dynamite also looms on the horizon.

2.2. 3D printed architecture products deriving function from Mashrabiya

A conceptual pod based on the Mashrabiya passive ventilation characteristics, the Microclimates project, proposed by Postler and Ferguson in 2009, adopts a Grasshopper algorithm to deform an Islamic pattern into a several standing 1- 2 meter pods that are claimed to passively cool the nearby environment if supplied with water from top. Depending on sand material supplied and printed by D-shape the concept targeted hot humid climates but was never built due to possible high cost. The second concept was recently promoted by Emerging Objects (Fratello 2014) in its cool brick product and wall assembly. Using ceramics and a porous form to act as a cooling screen in arid climate.

Both cases relied on the environmental quality of Mashrabiya screens but almost ignored the aesthetics and culture as well as the social domain Mashrabiya screens act within. A closer object to Mashrabiya social role can be seen in 3D printed textile as both serve a veiling role. However, structure complexity, material durability and surface quality are still a concern. Research in both ceramics and wood as well as other sustainable resources, like salt 3D printing, is ongoing and promising.

3. Digital & physical development of 3D printed parametric Mashrabiya

Currently, the authors' research is exploring the potential for 3D printing a culturally informed, environmentally reactive Mashrabiya screen system that leverages the manufacturing capacities of 3D printing. Notably, other means of fabrication were also explored, but none yield the flexibility of full customization in the way 3D printing can. In developing the reactive digital representation, Grasshopper 3D was utilized to redevelop the diagram that drives the geometries of the tradition Mashrabiya. Once the traditional zoning and functionality was understood, variation was embedded into the system to enable the programming to be reactive to the programmatic requirements of the interior architecture behind the screen (Figure 2). The system adjusts a set of apertures as well as adjusting the thickness of the members to set the desired transparency against the appropriate level of ventilation (Figure 3).

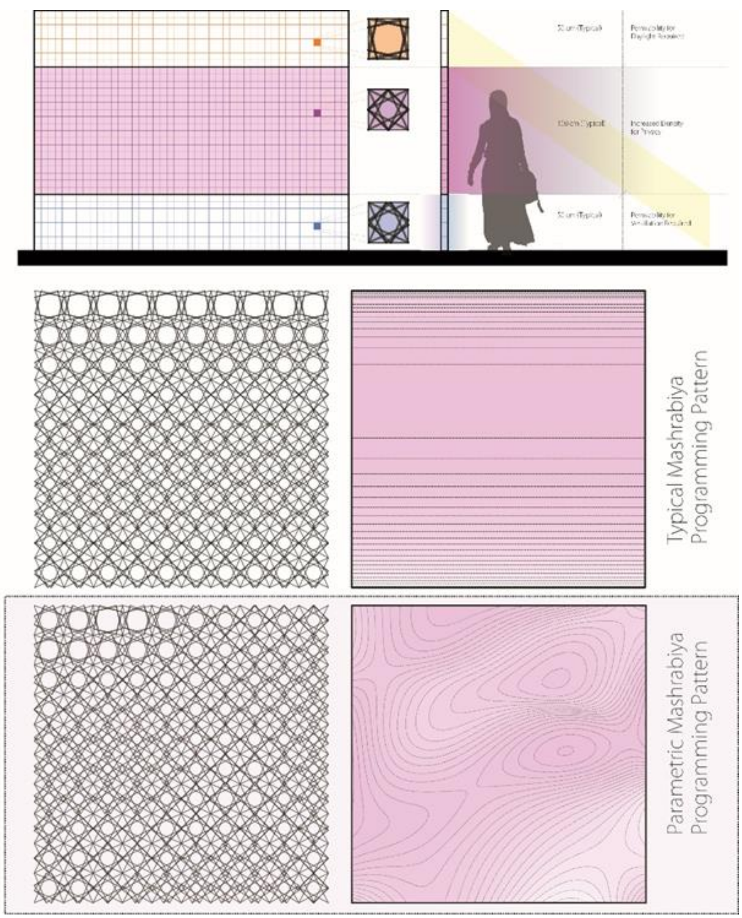

Figure 2: TOP, Diagram showing the traditional design and function of Mashrabiya. MIDDLE, Traditional mapping of components within system. BOTTOM, Programmable parametric variation.

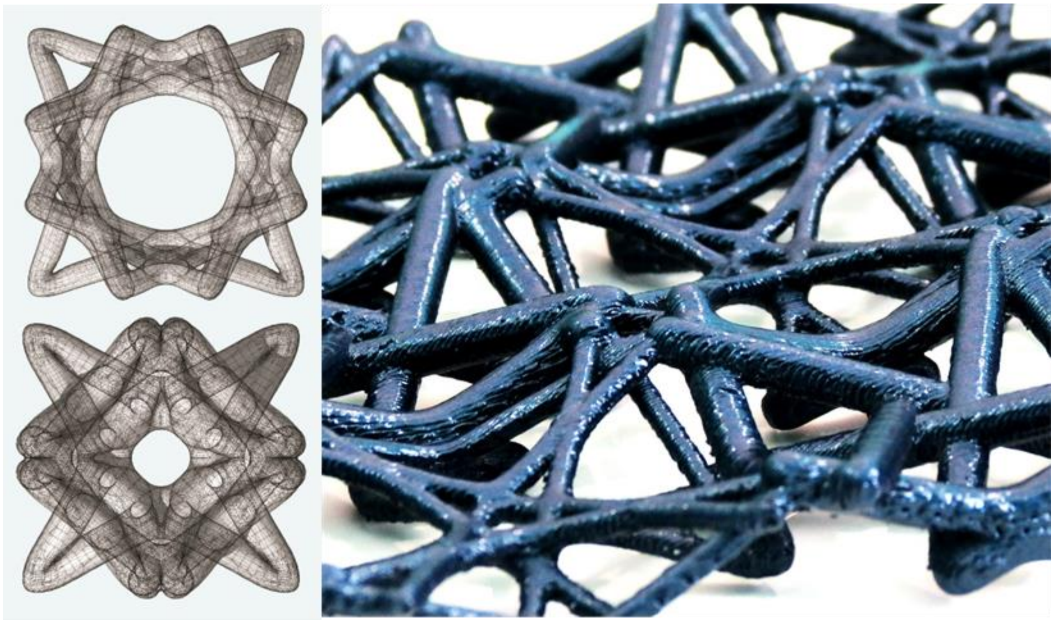

Figure 3: LEFT: Parametric Variation of parts through aperture and thickness. RIGHT: 3D printed ABS Mashrabiya prototype finished in automotive paint to enable exterior installation.

In concert with the digital development of the parametric model, ABS and SLS 3D printing have been targeted due the proliferation of the both technologies to test both functional parameters as well as the feasibility of the manufacturing process. These technologies are ideal given that parts can already be easily remade at low cost. Notably, both technologies are not designed for long term wear and tear, especially in the harsh environment of the Middle East. Resultantly, current research is exploring the application of automotive paint as a finish (Figure 3). Given the scale of the parts, the maintenance required of automotive paint and its durability in various climates represents a potential solution that would be appropriate for Mashrabiya scale architectures that are nonperforming structurally.

4. Methods for reviewing the developed work

A mixed method approach is used to gather and analyse information and data in this research. Both primary and secondary data has been collected to determine a SAFE value of 3D printed architecture and Mashrabiya based on the authors previous work. Primary data generated from semi structured interviews and focus groups were done during 2014-2015. More secondary data was gathered from 3D printing market reports, manufacturer's websites and literature case studies.

The semi-structured interviews included 25 Architects, designers, manufacturers and economic specialists. The focus group invited 6 members to discuss the topic and a proof of concept parametric model validity within a Middle Eastern country, Bahrain, as a research context. The SAFE value approach refers to Social and Aesthetic, Functional and Economic indicators, and is used in this research to get a framework that is then used to thematically analyse data gathered. A parametric model or a proof of a new Mashrabiya concept is also included as a result.

5. SAFE evaluation framework

In developing the framework for evaluating the value of the architectural product that will be resultant from the research the authors explored both architectural and product evaluation criteria. SAFE (social, aesthetic, functional and economic) was distilled and developed based on research within the literature review (Veryzer 1995, Biem & Jensen 2011) and engages targeted parameters to define success of a product in an architectural context. The four criteria evaluate these parameters:

- SOCIAL - Within the social and cultural setting, how does the design work respond appropriately to the urban context?
- AESTHETIC – How does the produced design fit into the fashion values and context of the given culture?
- FUNCTIONAL – What performative functions does the product achieve in the context of social/cultural, environmental/climatic, and emotional criteria?
- ECONOMIC – How feasible and sustainable is the production, transportation, assembly, and installation?

6. SAFE value of 3D printed Mashrabiya

Looking back at the case studies and the parametric Mashrabiya developed, the benefits of 3D printed Mashrabiya are analysed here according to the data gathered from various interviews and focus group within Bahrain as a case study of an Arabian Gulf country.

6.1. Social value

The social character of Mashrabiya has changed substantially as societies utilizing the architecture have evolved. With the loss of labour in their construction, Mashrabiya have become cartoons of their former designs. What was previously contextualised by climate, social obligation, and culture has fundamentally changes as the social character of Middle Eastern communities has changed after the oil boom. However, the Islamic religion’s appreciation to visual privacy is still a priority and a major concern in building and window shading solutions.

Analysis on data gathered from focus group indicated potential future social values of 3D printed Mashrabiya. The 3D printed Mashrabiya may functionally supplant the socially eroded versions that have resulted from the westernization of the Middle Eastern cultures. The applied patterning systems represent a technological solution (a value that is resultant from westernization) that can simultaneously re-address the social concerns of the architectural degradation of the Harim.

6.2. Aesthetic value

The richness of the Islamic patterns that once governed Mashrabiya screens has been considered a traditional aesthetic that modern construction has generally rejected, either through cartooning or through abandonment: Mashrabiya are being substituted with abstracted Islamic patterns that are subsequently “painted” onto contemporary facades or large reflective glass openings. New individualism and exhibitionism in building can allow mass customisation to be welcomed if designers acquire new digital skills and tools to enable them to design aesthetically appealing screens using new parametric software and 3D printing that simultaneously engages in architectural performance, which again addresses the westernization of Middle Eastern Cultures.

6.3. Functional value

Many new housing projects are designed with ignorance to sun direction. They foster large sized openings of fixed glass after relying mostly on AC systems and hardly relying on passive ventilation. This has created an extra amount of sun penetrating the interior. Shading devices are of extreme importance in hot countries. A 3DP Mashrabiya may provide complex geometry and aesthetics that best serve and aesthetically and functionally metamorphose to owners needs and design desires as well as respect the huge emotional and religious attachment of Mashrabiya privacy role in these communities. Strauss (2013) condition the development of the technologies from sophisticated prototypes to reliable one to have an impact on building envelopes and facades.

6.4. Economic value

The economic validity of a 3DP Mashrabiya is highly dependent on the material, scale and cost of production in comparison to mass production using CNC or GRC moulds. Lattice structures are analysed by Wohlers report (2014) to reduce cost as less material is used. However, with the cost difference from a CNC screen of $930 to a 3DP Mashrabiya of $3000 by SLS or $ 2400 by PMMA offered by Voxeljet. Specialists would say it is yet very early for architecture to be a valid substitute to mass production elements. However, when it comes to Mashrabiya and the intensive labour and craft it requires against the value of the digital craftsmen design freedom, 3DP was agreed to have a benefit as supported by the focus group members, and the interviews. Moreover, concrete 3DP and FDM by d-shape or PMMA by Voxeljet are already steady in this field. The prediction of a lower cost in the coming 5 years for 3DP Architecture with polymers is nearing this threshold perhaps but not in metals. An alternative option suggested to produce the window screen is to use the lost-wax method that may be economically feasible. The fact that 3DP can speed up the prototyping process but not the manufacturing process of a product can add a cost for time spent versus quality achieved. Strauss (2013) claims that by 2020 the technology will change existing building details

6.5. SAFE value of 3D printed architecture and 3DP Mashrabiya

By examining the values offered by SAFE, it is evident that 3D printing in architecture might not be yet applicable in enormous building projects as printers size might be enormous and difficult to control but smaller products like columns or screens are viable. 3D printed Mashrabiya screen is proven to offer social aesthetic and functional benefits that may be economically viable in the coming 5 years.

The holistic approach of looking at the social, aesthetical, functional and economic issues of 3D printing potentially enhances the suitability of the product to be 3D printed. This value is of high importance when looking at architecture products that are aesthetically appealing but not functional or simply out of the cultural concept of its potential end users.

7. Conclusion and discussion

In the post digital age, how we design and make has been called into question as new considerations in culture as well as performance have found themselves being codified. In developing the parametric models of both our culture and our construction we discover the fundamental rules at play, rules that govern the social and aesthetic constructs that we are a part of. Never before has there been such a global community and its impact is being felt across cultures. Design and making have become liquid through ubiquitous computing and digital manufacturing. These malleable tools suggest the distillation of both construction detailing and cultural/social identity and awareness.

The constructions that have been developed (both digital and physical) explore the methods that are currently available in light of the emerging disruptive technologies. While there is evidence to suggest that these constructions can be made through other means, the adaptability of 3D printing enables the execution of mass customized constructions regardless of siting conditions. The research suggests that not only is the method for production a valid solution but that it also enables the crystallization of cultural moments: the construction is direct result of the programmed values in the design.

As the research develops, present and future resultant parametric models and constructions methods suggest the production and fabrication of socially and functionally intelligent architectural products and also the evolution of codified systems to embody evolving cultural values. Each model provides a snapshot of the culture, as it is understood by the research; interrogating the passage of light, control of airflow, temperature of air current and humidity, and the privacy of the woman's quarter (Harim) in courtyard houses in the Middle East. Extending this logic into future architectures might not only save archetypes, but also more clearly reveal the socio-economic, cultural and performative criteria that informed their forms.

Lastly and perhaps most importantly, cultures do not exist in stasis. New questions regarding the codification and construction result from the inquiry into contemporary building. Building codes that were non-existent in the historic models require the reshaping of the parametric design to accommodate for foundational architectural issues such as egress and must be addressed in the new models. The design work and culture is fated to change and evolve. These new modes of design production represent an opportunity to not only codify the products themselves into mass customized products but also suggest that we might be able to reflect on cultural values of both past and present and program new trajectories in social development.

References

Almerbati, N., Ford, P., Taki, A., Dean, L. (2014*) From Vernacular to Personalized and Sustainable: The Value of Additively Manufactured Window Screens in Middle Eastern Dwellings: Proceedings F. Madeo and M. A. Schnabel (eds.), Across: Architectural Research through to Practice: 48th International Conference of the Architectural Science Association 2014*, the Architectural Science Association & Genova University Press, 479–490.

Anderson, J. and Tang, M. (2011) *Form Follows Parameters: Parametric Modelling for Fabrication and Manufacturing: Proceedings in 16th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA)*, 91-100.

Biem, A. and Jensen, K.V. (2007) Forming Core Elements for Strategic Design Management: How to Define and Direct Architectural in an Industrialized Context, *Architectural Engineering and Design Management*, 3(1), 29-38.

Choma, J. (2010) Contested Boundaries: Digital Fabrication + Hand Craft *in SIGRADI: Disrupcion, modelacion y construccion: Dialogos cambiantes*.

Crolla, K. and Williams, N. (2014) *Smart Nodes: A System for Variable Structural Frames with 3D Metal-Printed Nodes, ACADIA 14: Design Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 311-316.

Dritsas, S. and Yeo, K. (2013) R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Undrawable Architecture: Digital workflows for the conservation of heritage buildings and the discovery of digital tectonic: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 833–

842. The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

Fathy, H. (1986) *Natural Energy and Vernacular Architecture*, the United Nation University by the University of Chicago Press.

Fratello, R.S. (2015) *Cool Brick*. Available from: http://www.emergingobjects.com/projects/cool-brick/ (accessed 5 June 2015).

Moussavi, F. (2008) The Function of Ornament i*n Kubo, M. (ed) The Function of Ornament*, Harvard Graduate School of Design.

Peters, B. (2013) Building Bytes: 3D-Printed Bricks in ACADIA 2013 Adaptive Architecture, 433-434.

Rael, R. and Fratello, R.S. (2011) *Developing Concrete Polymer Building Components for 3D Printing, ACADIA 2011: Integration through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 152-157.

Strauss, H. (2013) AM Envelope: The Potential of Additive Manufacturing for Façade Construction. *Architecture and the Built Environment*, 1.

Veryzer, R. W. (1995) The Place of Product Design and Aesthetics in Consumer Research in Advances, *Consumer Research*, 22, 641-645.

Wohlers Report (2014) 3D printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress report. Wohlers Association.

yhbm.com. Winsun Decoration Design Engineering Co. Concrete 3D printing homes technology. Available from: http://www.yhbm.com/index.php?m=content&c=index&a=lists&catid=67 (accessed 5 June 2015).