Digital Fabrication and Crafting for Flexible Building Wall Components: Design and Development of Prototypes

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Abstract –

This research aims to explore and reflect the links between form, function, material and fabrication to develop and assemble more adjustable and flexible building walls. The interconnection of these main aspects of creation is particularly driven by the raising prominence of digital and computational tools in the context of design and fabrication. The new trends in digital fabrication and construction industry have fundamentally impacted building envelope components design with a shift in emphasis from flexible structures to envelope and from form to performance. The objective of this research is to develop new prototypes for more lightweight, dynamic, possibly interactive body envelope with the contribution of digital crafting. The first wall prototype was designed and assembled in the laboratories of University of Minho using CAD and subtractive machining to produce the parts and apply physical tests to the wall. Based to that experiment the second prototype is digitally developed and generated with additive manufacturing; presenting the development process; as an attempt to build an entire envelope from printed components.

Keywords –

Digital design; Digital fabrication; Crafting; Building wall components; Component design; Rapid Prototyping

1 Introduction

Innovations in material, design, and fabrication processes are currently thoroughly researched and applied in various areas. Digital technology and digitally driven fabrication are now the norm of turning architects, designers and researchers towards new concepts of design thinking and manufacturing that subsequently lead to more advanced architecture. Digital fabrication with crafting techniques can evolve the creation of physical prototypes; evaluate the constructability, material behaviour and selection as well as aesthetic qualities. There is a strengthened and more correspondent relation between the development and fabrication process combined with a higher flexibility considering the geometry, process, and material driven design; not only in the phase of design and manufacturing but also in the final step (Lu B., Li D., Tian X. 2015).

Wide range fabrication technologies and composite materials have been developed and started to impact architecture for their high performance characteristics. The intelligent control and automation of processes break up the strong limitation of variation in material, structure and form in the traditional industrial production. Students and professionals design with three-dimensional digital tools and, through this technology, design and construction are inextricably woven together in a continuous feedback loop. Based on the principles of open source, computer numerical controlled CNC production data is distributed and further developed via the Internet and new knowledge regarding materialization is being shared. Ideally, production knowledge is shared using Creative Commons licenses and a global network of mini factories is created with these networked digital production methods.

In the realm of building components, the walls are providing primary site of innovative research and physical tests. Building partition and envelope wall components are among the elements in a building that can be improved for better performance and more integrated with the other building systems. The wall component prototype is related with the geometry, the function and the materials made up to perform the required design. One of the key innovations in the field of building construction and building physics has been the emergence of high-performance materials (Aksamija A., Snapp T., Hodge M., Tang M.2012). The criteria to estimate the potential of the technologies for their application in the wall are weight, rigidity, and load-bearing capability of the parts.

The advancements in Additive Manufacturing AM technology is proceeding towards customizing products in design, production and material selection; have hugely impacted the way 3D printing is viewed and relied upon by engineers, designers and manufacturers and lead increasingly construction evolutions. 3D printers are nowadays substantial for experimenting prototypes and approaching the end-use production parts in hundreds of plastic, metals and other printing materials (Hager I., Golonka, A., Putanowicz, R. ICEBMP 2016).

2 Prototype Design: Digital Design and Crafting

Building designs and prototypes are not born out only digitally, but they can be realized digitally and to come to exist in faster time and with more accuracy. With the aid of computer aided design (CAD) and computer-aided manufacturing (CAM) technologies rapid developments have broad in building design, construction practices and rapid prototyping. Digital design is the early step of the work that provides CAD mother model. Digital processes starts with analyzing the information data structurally for all parts of the prototype to prepare them for CAM software, the second step is translating the analyzed information to command the fabrication machines to produce the physical modeling either on-site or in the factory; this workflow is known as "File to Factory". The focus of the technology descriptions will lay on the methods to produce components from different materials that contribute to a wall partition.

The fabricating processes due to the manufacturing methodology can be categorized as: subtractive manufacturing (CNC) and additive manufacturing (3d printing). Both are considered active tools for Rapid prototyping.

2.1 Subtractive Manufacturing

Subtractive manufacturing also known as CNC machining, involves the process of removing a specified surface or volume of material from solids and also milling axially; by using cutting devices; either by electro-, chemically- or mechanically-reductive also advanced CNC (multi-axis milling).

In axially constrained devices, the piece of material that is milled has one axis of rotational motion such as lathes. There are millings of three-dimensional solids that have the ability to raise or lower the drill-bit, to move it along X, Y and Z axis, removing materials volumetrically. There are also four- and five-axis machines when milling special shapes.

From the advantages of subtractive processes, can include a wide selection of end-use materials; offer a variety of surface finishes, good dimensional control and fast with a high degree of repeatability suitable for end-use manufacture. The disadvantages are related to some material waste, and geometry restrictions; certain geometries such as a sphere as well as complex geometries Additive are still the choice.

2.2 Additive Manufacturing

The term Additive Manufacturing also referred to nowadays as synonym 'layering manufacturing' and '3d printing', a process by which digital 3D design data is used to build up geometry in layers by depositing and bonding materials one layer at a time. The AM build the geometry by depositing with the benefits of robotically controlled and free-form manufacturing. The size and speed of the adding nozzle and the design size directly affects the build time, therefore, design, size, geometry, function, material and application of the component are substantial for selecting the right technology and material for the prototype. Materials available with 3D printing technologies range in heat deflection, chemical resistance and durability and material viability greatly depends on design, application and desired product life. To determine the material and 3D printing process which will best support one application, the most appropriate materials and technologies should be considered, as mentioned on Table 1 Adapted from: https://www.protolabs.com/resources/white-papers/rapid-prototyping-processes/

Table 1. Interaction between materials and techniques on digital fabrication

Rocess	Description	Finish	Example Materials
CNC	Machined using CNC mills and lathes	Subtractive machined	Most commodity and engineering-grade thermoplastics and metals
LASER	Machined using Laser head	Subtractive machined	Wood derivatives, Cardboards, PMMA and metal plates
SLA	Laser-cured photopolymer	Additive layers of 0.05-0.15mm (typical)	Thermoplastic-like photopolymers
SLS	Laser-sintered powder	Additive layers of 0.10mm (typical)	Nylon, TPU
DMLS	Laser-sintered metal powder	Additive layers of 0.02-0.03mm (typical)	Stainless steel, titanium, chrome, aluminum, Inconel

FDM	Fused extrusions	Additive layers of 0.15-0.35mm (typical)	ABS, PLA, PC, PC/ABS, PPSU
MJF	Inkjet array selectively fusing across bed of nylon powder	Additive layers of 0.10-0.20mm (typical)	Black Nylon 12
PJET	UV-cured jetted photopolymer	Additive layers of 0.015-0.030mm (typical)	Acrylic-based photopolymers, elastomeric photopolymers
DDM	Direct extrusion	Additive layers (variable)	Concrete, clay, plaster
IM	Injection-molded typically using aluminum tooling	Molded smooth (or with selected texture)	Most commodity and engineering-grade thermoplastics, metal, and liquid silicone rubber

The selection criteria among the described technologies will be on the basis of product delivery, material ,tolerance ,cost ,quantity of product, and desired needs of product whether its speed, function or a specific material (Yadav, K., Sharma, K. R., and Anand, D. JMSME, 2015).

2.3 Digital Crafting and Material Selection

Although both Additive and Subtractive have similar workflow method but still there are notable differences. The connection of digital design and digital manufacturing can be resumed as 'Digital Crafting', which describes the combination of work techniques typical of craftsmen with computer-supported processes. The way of honoring material and its strong – but ever changing – relation to manufacturing processes leads not only to new design aesthetics but also to a new, crafting oriented way of design thinking.

The principles of digital design and manufacturing processes are rather linked to a way of craft production than industrial processes as they emphasize the qualities of the materials used and provide higher flexibility during the development and production process.

Smart materials have been applied in architecture, but rarely so that the responses give a global effect on the performance of the entire building. The materials as well as the technical equipment for AM technologies have been continuously developed since. A new market opened up that is still growing today. Choosing the right materials and techniques is substantial for creating highly customized building components.

Material-technology partnerships expanding more nowadays as material chemistry explored more as well as mechanical properties can be evaluated very precisely. As stated in the differences between additive and subtractive manufacturing, materials are defined by the technology. 3D printing transforms materials through either external heat, light, lasers or other directed energies depending on the printer type. The ability of a material's mechanical composition to react positively to a certain directed energy marries that material to a technology which can deliver the desired change.

The new trends in advancing technologies encourage products made from more environmental friendly material. The performance of materials varies and to fabrication technologies and processes the material needs to be efficient in terms of mechanical properties and design capabilities. For AM developments, materials correspond with developments in methods and machines; as the workflow also improves to achieve more benefits from materials, therefore, material selections expanded to include ecological and less harmful materials.

Smart materials have been applied in fabrication as they can just replace conventional materials been used with the advanced machines, whilst smart properties can perform additional benefits. An example of this is 3d painting with nano-particles of titanium oxide, which not only protect the surface but also reduce pollution in the surrounding environment through photo catalytic behavior.

Emerging digital processes are beginning to impact the profession of architecture in a manner similar to what has occurred in other creative/design disciplines providing new methods to evolve the practice of architectural design. The study presented two models to demonstrate the technical process used to translate digital designed models to manufacture descriptions and physical assembly.

3 Smart Building Component Design Using Subtractive Techniques

The first case study presents the research process of an innovative solution for partitions, designated as AdjustMembrane, developed within a Portuguese Foundation for Science and Technology funded research project. The proposed system is a modular non-loadbearing wall, tensioned between the pavements and ceiling slabs, which are used as anchoring elements. It allows several advantages, related with the weight reduction to achieve good sustainable indicators, such as the reduction of construction costs, energy, and materials. It is easy to recycle and reuse, allowing easy assembling and disassembling [Mendonça, Macieira and Ramos, 2014].

This solution of non-structural partition wall is characterized by a structure in tensioned belts that serve as support for the two-stage assembly of panels with a core in fibrous material, as showed in Figure 1.

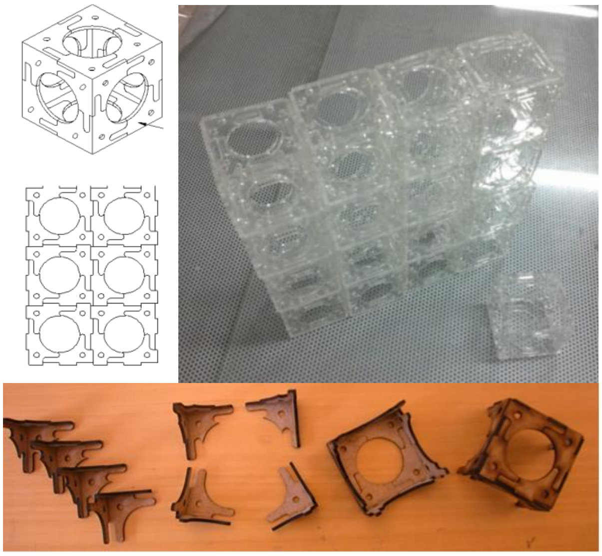

Figure 1. Component design with MDF (Laser cutter)

The core may include a grid (Figure 2) - with modules that can be subtracted or added to allow the panels to adapt to the dimensional requirements of the space to be partitioned and which at the same time serve to reinforce and give rigidity to the panel.

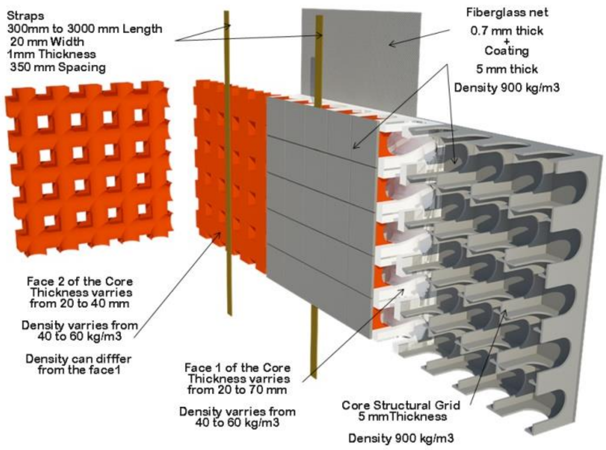

Figure 2. Prototype design and system assembly

The core of the panel solution is characterized by having vertical grooves in the interior allowing the integration of water, gas and electricity networks; the core shall consist of a material fibrous / porous so as to function at the same time as thermal and acoustic insulation of the facilities and between the various compartments.

The typological suitability required that there were a translucent variant of the study material for the partition wall. To do this, the prototype must be carried out with the application of a translucent material and performed acoustic and light transmission tests.

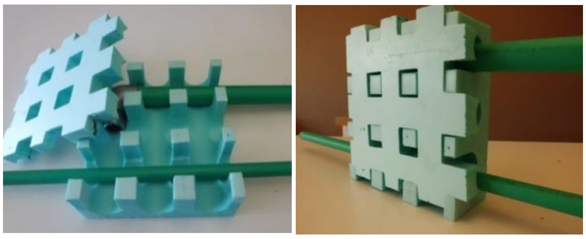

Figure 3. Component manufactured XPS (CNC hotwire cutter 2D)

4 Smart Building Component Design: Digital Fabrication and 3D Printing

The research objective is to build and develop components by conceptualizing the component assemblage and bringing it to the physical modeling with the use of 3d printing. The concept of the development is another advantage of digital fabrication when extending the future possibilities to the real scale. Although the components generated here are physically small, the study concern is how to build assembly descriptions based on real-world construction.

The most popular 3D printing manufacturing technologies can be found as PolyJet, Stereolithography (SL), Laser Sintering (LS), Fused Deposition Modeling (FDM) and Direct Metal Laser Sintering (DMLS) and more. For the study Polyjet was used for printing the component.

The aim of this case study design is to undergo the considerations of developing printing and developing the prototype through the following:

4.1 Prototype Development Process

As the study is to propose prototype development for a digitally driven fabrication framework, an exploratory model on the usability of a prototyping-process is designed. The analytical data have continued with the objectives of the first case, more flexible and manual assembling building envelopes, therefore, the development process is considered a design to manufacturing process with Additive (Fig 3).

4.1.1 Data Preparation for Prototype By Additive Manufacturing

Data preparation is identical to other AM processes, with an exception to a supplemental post- processing step which is optimizing the generated printing path of the precipitation head so as to decrease the time of printing in addition to possible overprint of materials because of orifice proration that is on and off, by diminishing the non-printed motions of the precipitation head. A 3D MAX model was designed for the printing component, transformed as an SLT document format, slicing is performed using a coveted layer depth, a printing track is produced for each layer, and for the printing a G-Code document is manufactured.

4.1.2 Application Process

Many materials which are printed by 3D system provide biocompatible features, abilities for sterilization, licensing from FDA for skin exposure, toxicity, fire retard, heat fume, and resistance to chemical agents or other credentials that might be serious for your plan. When a material and 3D printing process is selected for the design, it will be mandatory to guarantee that your substance is capable of delivery upon these credentials.

4.1.3 Function

Stringent investigations are performed for 3 D printing substances for answering the stress types it can tolerate and the grade of the terrible environment the substance will surpass in. The fact that the material is able to act in a desirable employment depends partially on layout.

4.1.4 Geometry

As it is previously stated, substances which are printed by the 3 D technology cannot be isolated from their concordant technology. Moreover, every technology regardless of its kind (Like FDM, stereo lithography or Laser Sintering) is proficient in presenting specific geometrical fulfillments. While selecting the technology of substance and 3 D printing, dimensional tolerances, minimum feature fulfillment as well as thickness of the wall of the layout should be taken in to consideration.

The Geometry development process of the building wall component design Consider the dimensional tolerances, minimum feature execution and wall thicknesses of your design when choosing a material and 3D printing technology. The thickness for this component was 100mm.

Figure 4. The Geometry development process of the building component design

Printed designs can result in fine surface finish products with the right post-processing. Some materials may be better suited to certain post-processing methods than others – heat treating stainless steel versus post-curing a photopolymer, for example.

During the design process flexibility and sustainability of applying composite envelope configuration were assessed through Digital designing and optimization tools that can help to identify assembly and disassembly tolerances and analysis of performance objectives.

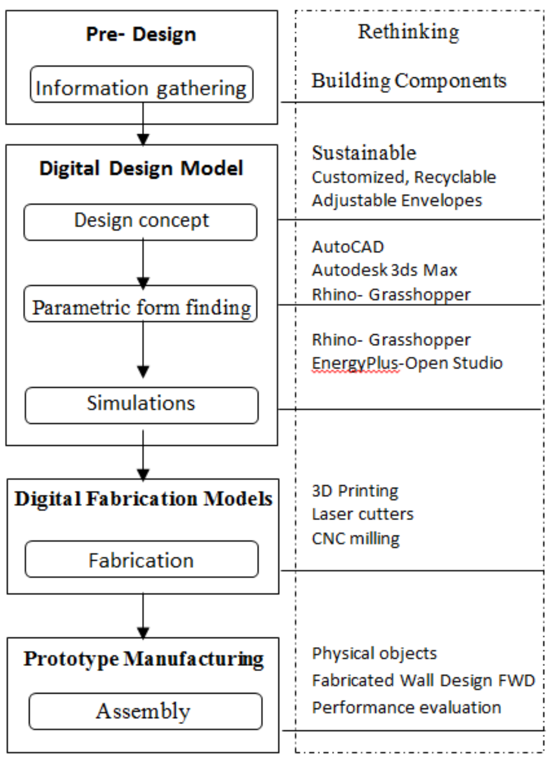

Figure 5. The development process of the building component design. Adapted from “Re-Skinning: Performance-Based Design and Fabrication of Building Facade Components” (PERKINSWILL, 2012 / VOL 04.01)

4.2 Assembly Description

The printed parts can be manually attached to become a base unit easily to connect with the printed tube bars. When combining more units, they formulate a panel, with repeating the process then a standing wall structure ready to assemble the electrical plugs and wires and also the mechanical piping. Then the system will be ready to apply panels to.

Figure 6. 3D printed component prepared for assembly

The 3D printing components will be subjected to rigorous testing in order to answer the kinds of stresses it can endure and for more future developments the components can be coded and marked with the nodes of intersection with adjacent layers of structure.

The units are designed to be fastened to each other and the final structure will be completely self-supporting and will not require secondary scaffolding. The final product is the scale of a room and is composed of 600 3D printed parts.

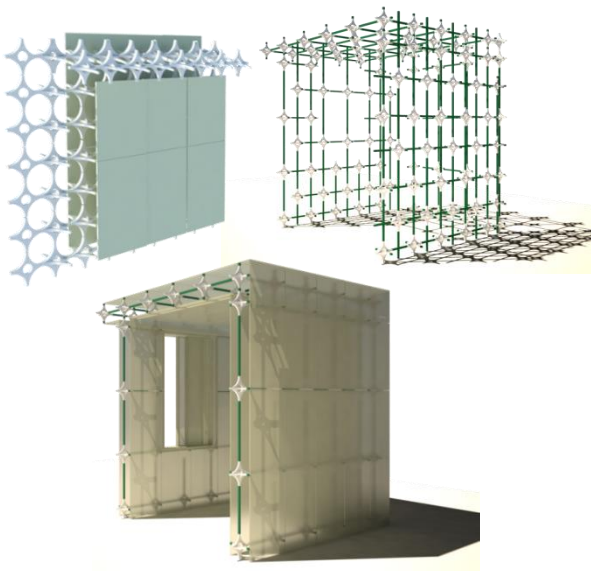

Figure 7. The FWS to be assembled, the Designed and rendered with 3cDs Max

4.3 Digital Fabrication and Performance Design

The partition wall system Adjust Membrane presents ease integration of facilities, good mechanical principles, and good acoustic properties and modularity. Experimental prototypes were executed to test the mechanical properties, the access to the placement of installations as well as the integration of the structural grid and the way of installing the partition wall. The assembly process has been tested allowing to define the expected to adjustments, in particular with regard to the connection to the structural straps.

The mechanical properties to be tested for a printed sample of a panel consisting of 3 attaching units and to determine the physical test in the Construction and Technology laboratories of Uminho, Structural links have to be more detailed and investigated, with trials and simulations. The connection between panels should be tested in prototype as well as possible coating application.

5 Conclusion

The study demonstrates the potential of digital design and fabrication, and crafting techniques to develop building envelope components to become more adjustable, flexible and sustainable. Digital design tools offer guidance in analyzing the manufacturability of the building components. The principles of digital design and manufacturing processes are rather linked to a way of craft production rather than industrial processes as they emphasize the qualities of the materials used and provide higher flexibility during the development and production process.

New developments in advanced computational tools and methods are offering unprecedented ways for design exploration and evaluations. Performance-based design that integrates simulations and environmental analysis in the design process has an advantage over traditional design methods, because it allows a certain design iteration to be evaluated against different solutions. Also, digital fabrication techniques allow for creation of physical prototypes, which can be used to evaluate constructability, material behavior and selection as well as aesthetic qualities.

Contribution of digital crafting in the generation of design and building assemblies is an integral approach in improving design process, with the direct connection to practice and research. The innovative products can be developed rapidly with digital design and fabrication of numerous representation tools and production software. Such uses of technology strengthen the ties between design and craftsmanship and motivates to a continual evolution of the field of architecture with construction companies and universities supporting such innovative trends of research and design.

The study on typological suitability, functional and structural performance in both wall solutions presented in this paper will be subjected to more analytics, performance simulations and later experimental testing. There is a strengthened and more correspondent relation between the development and fabrication processes combined with a higher flexibility considering the geometry: in the phase of design and manufacturing but also in the final shape.

Acknowledgments

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