A Closer Perspective on Fabrication Realities

Kareem El Sayed Mohammad¹, Mohammad Assem Hanafi², Mohammad Nasr³
Faculty of Engineering, Alexandria University, Egypt.
¹arch_kareem_elsayed@yahoo.com, ²mahanafi@hotmail.com, ³targetwork@yahoo.com

Abstract. Digital Fabrication has arguably stirred the return of the architect to the long-held position as a master builder. The close engagement with materials offered by the digital fabrication technologies places necessary limitations and calls the architects for a deeper understanding of and awareness about the fabrication realities during the design process. The research conducted uses parametric modeling for the alteration of the design according to a wide range of influences, one of which is fabrication. This paper offers a close perspective on some fabrication necessities and limitations that emerged through the manufacturing of a number of scaled models of a parametrically designed shed and a full scale pavilion. The scope of this work falls into the realm of physical testing, tolerance, structure and assembly. It also points out the fabrication parameters that were part of the digital setting used to create the physical models. The paper argues that craft is still practically alive when deploying digital technologies as it has been ever present in the pre-digital era.

Keywords. Digital fabrication; tolerances; parametric design; assembly; Laser cutting.

INTRODUCTION

The use of parametric design tools and digital fabrication technologies deeply transforms the very nature of the design process. Architects involved in digital practice ought to get deeper understanding and better knowledge of real issues related to these technologies. Through the work of the first author’s thesis entitled “Digital Fabrication in Architecture, Construction Aware Design”, some hands-on experience was obtained in the field of digital craft.

As Renzo Piano once said, “An architect must be a craftsman. Of course any tools will do; these days, the tools may include a computer, an experimental model, and mathematics. However, it is still craftsmanship – the work of someone who does not separate the work of the mind from the work of the hand. It involves a circular process that takes you from the idea to a drawing, from a drawing to a construction, and from construction back to idea.” (Buchanan, 2003).

Craft is very much alive when deploying digital fabrication techniques; the potential of digital fabrication does not eliminate the need for the craft-worker who understands the final product and from the beginning works with the architect to imagine how to create it (Gang, 2008). This paper takes an approach of reconstructing the gap between the architect and the built form through a deeper understanding of material behavior and fabrication potentials. It displays and discusses some fabrication necessities and limitations that emerged through the manufacturing of two applications. The first is a number of scaled models of a parametrically designed shed and the second is a modular full scale pavilion that is easy to assemble and disassemble.
BACKGROUND
As a part of the first author’s thesis research on construction aware design, the work conducted in the first application uses parametric modeling for the alteration of the design according to a wide range of influences, one of which is fabrication. The set of scaled models were intentionally meant to be fully parametric, from the form generation phase to the final preparation for Laser cutting in a paperless process. On the other hand, a semi-parametric approach was used for the design of the second application i.e. full scale pavilion. Regardless of the stage at which parametric modeling tools were used, both applications show an important urge to understand the limitations and potentials of digital craft tools. Axel Kilian (2003) argues that there is some sort of resemblance between conventional craft and digital technology concerning the ease or difficulty of creating certain shapes. Some parts need to be redesigned in order to be fabricated efficiently. This particular aspect is of central significance to this paper.

Laser cutting
Laser cutting is one of the most commonly used fabrication technologies in the field of digital craft. Its versatility and availability on local markets promotes using it not only to fabricate final products, but also as a design development tool for design models. Generally, nonmetal cutting has three requirements: (a) a focused beam of energy at a wavelength that will be absorbed by the material to be cut so that melting, chemical degradation, or vaporization can occur; (b) a concentric jet of gas (usually compressed air) to remove cut by-products; and (c) a means of generating cuts in straight lines or curved patterns (Belforte, 2001). The main parameters controlling the laser cutting operation are beam diameter, laser power, traverse speed, gas composition, material thickness, reflectivity and thermo-physical properties (Steen, 2003). Schematic (Figure 1) shows Laser cutting quality factors.

Organic materials (e.g. plywood) are generally decomposed by laser light. The energy required to do this is usually much lower than that required to melt inorganic substances, so cutting can often be done at high speeds or with lower power lasers. The large volume of the decomposition products causes some problems: Gases in the kerf -material cut away- have trouble escaping, limiting process speeds and degrading edge quality. In addition, many organic materials evolve toxic compounds during laser cutting. These effluents must be handled in a manner to eliminate hazards to operators and to the environment. Steen (2003) provides a detailed theoretical and practical examination of Laser related material processing techniques within an industrial environment.

Through the use of Laser cutting to manufacture the scaled models and the pavilion across different scales, and in different design stages, some defects and drawbacks were noticed. The paper presents hands-on experiences and gets into intimate details about building the models in general and about Laser cutting in specific.

Figure 1
A schematic for Laser cutting quality factors.
APPLICATION (1): PARA-SHED SCALED MODELS

Setting parameters (parameterization)
Planning the set of controlling parameters is always the most challenging part of preparing the parametric setup. These parameters change from one project to another. It is critical neither to under-constraint the design by creating a huge number of variables and parameters nor over-constraint the design in a manner that makes it difficult to choose a suitable instance. According to Almusharaf and Elnimeiri (2010) the controlling parameters can be categorized mainly into: Geometric, Functional and Structural. In some cases, there exist another set of auxiliary parameters that are dependent on the scale of the project.

It is commonly known for parametric software users that two categories of parameters are to be differentiated: parameters that are determined manually by the designer as input data and parameters that are determined and optimized automatically within the parametric schema. The former include in our case: number of sides of base geometry, radius of canopy base, lower section height, upper section height, cap height, canopy overhang radius (Figure 2). These parameters were set and developed to capture a vast array of morphological schemes. They were responsible for the overall geometrical and dimensional configuration of the designed shed, and up to this stage, independent from material properties and behavior.

Design approach
Using waffling as a design and material technique that originally stems from sectioning (Iwamoto, 2009), the designed shed was cut in the digital parametric model into planes in both X and Y directions. The planes were intersected and cross half lap joints (notches) created (Figure 3). This waffling technique is adequate for the creation of the scaled models, but is surely not applicable in the case of full scale construction due to a number of limitations: most prominent of which is the constructability and handling of large parts besides the available stock sheet sizes. The selection of this design technique was deeply intertwined with using Laser cutting, as the process of design involved extracting two dimensional profiles from the digital model and nesting them on a sheet material.
The waffling algorithm gives the designer the ability to:

• Specify the uniform spacing for each of two orthographic cut planes informed by the number of planes sufficient to maintain the structural integrity and the visual intensity of material, besides providing adequate shading.
• Specify the rotation angle of the orthographic cut planes to the designed form.
• Change the notch size as a direct representation of sheet material thickness from which the tolerance is considered as an integral part.

In addition to these so-called soft factors, a number of automated optimization parameters were controlled automatically using digital algorithms. These include:

• Arrangement of profiles by orienting and spacing them on world xy plane.
• Creation of cross-half lap joinery (notching).
• Numerical coding (labeling the profiles in both orthographic directions).

In the scope of this application, only parameters directly related to the fabrication process are discussed such as: numerical coding, material thickness (notch size), assembly sequence and logic.

NUMERICAL CODING

In free form architectures, composed of large numbers of unique pieces, it becomes very important to properly manage this quantity of parts for final assembly. The possibility of designing a simple script or Grasshopper definition that encodes the profiles in both directions with different hierarchal codes is beneficial. It could be simply a number or a combination of text and number to address pieces. If the object comprises of different main parts each divided into pieces, then we can name main parts, so we can use these names or initials with numbers to address the pieces (i.e. upper_section_01).

At this stage of design, a paper model was used to test the numerical coding and the sequence of assembly in an attempt to formulate a logical hierarchy. The paper mockup profiles were prepared, nested and printed on 350 gm paper using a typical plotter. They were then manually cut and assembled. Different approaches to the assembly process were tested, starting from the central parts to the outside or vice versa. Using the paper model, some evaluations and alterations were made to the overall form. It was a great tool to comprehend the form and its assembly. The process went together well, but comparing the physical output with the digital model revealed areas that could have been better designed.

Managing tolerances and constructability

An important aspect related to Laser cutting technology discussed with the fabricator was the laser beam width (average 0.002 inch) and its related kerf width (material cut away). Beam quality and focus, gas assist, material thickness, and process rate determine kerf width (Belforte, 2001; Ion, 2005). These factors are interrelated, generating a high number of process variables. The narrowness of the kerf is a major advantage of the laser process. A narrow kerf allows cut patterns to be nested as close as one beam diameter apart, an effective way to reduce scrap material.

Discussions with the fabricator showed that Laser machines are capable of moving the focal point of the laser cone up and down in Z direction depending on the thickness and nature of the material used. Changing the beam waist position relative to the work-piece surface modifies the power intensity at the surface, thus affecting the size of the kerf. Some materials emit large amounts of gas on vaporization by heat; therefore the focal point is placed at midsection height, leading to a narrower intersection with Laser cone. This typically means a narrower kerf width thus lower emissions of vapor, i.e. narrower tolerance.
Some other materials emit lower amounts of gas on vaporization, and thus the focal point could be placed at the bottom surface of the sheet material, thus a wider cone is in contact with the material. This kind of slight changes can inform the digital parametric model by assigning different values to material thickness parameter to account for exact kerfs and tolerances.

The initial design intent was to use three millimeters thick plywood sheets with integral joining assembled using friction only. The material thickness parameter was planned during the parameterization process as a user-defined value, in order to be subject to and informed by all possible influences.

The material thickness parameter was set to this exact value and the profiles prepared for cutting. After cutting and during assembly, it was clear that the profiles were loose. After some trials and negotiations with the fabricator, a decision was made to inform the digital parametric model from the realities of material. Analog and digital micrometers were used to measure the exact thickness of the plywood sheets, which was variable across the range from 2.6 to 2.8 mm instead of being exactly 3.0 mm. The plywood sheets themselves were not of constant thickness. Thickness imperfections were not planned for previously but were managed by manipulating a sliding scale, a huge advantage to a parametric model.

**Physical assemblies**

When the structure was assembled, one issue evolved that was misleading in the first paper model and all the subsequent trials and mockups. At the fabrication facility, numerous trials were made to test the assembly of three or four profiles at most. On the full assembly of all members (47 profiles), the overall structural tolerance was tight compared to each single member tolerance due to an effect called *accumulated tolerance* or *tolerance stack-up*. This term is used widely by engineers to describe the problem-solving process in mechanical and production engineering of calculating the effects of the accumulated variation that is allowed by specified dimensions and tolerances (Fischer, 2004).

The first mockup model profiles had to be manually sanded in order for the whole structure to fit together (Figure 4). The process was laborious and time-consuming, and had a negative impact on the edge quality and the final surface finish of the wooden profiles.

Profiles in two perpendicular directions assembled with no sufficient tolerance lead also to a *warping effect* of members which can also be strengthened by temperature variation and natural expansion of material. The solution to this problem would be either to increase the tolerance of the notches, or cut the longest profiles into parts to create an expansion joint. The former solution has a strong limitation which is to maintain the frictional
force required for the assembly to preserve its coherence. A decision was made to cut the longest profiles into parts, with a minimum of 5 notches per part, to sustain the friction needed for snap-fit assembly.

**Short findings**

It can be said that efficiently planning the fabrication parameters into the parametric model, caused a great deal of time saving, e.g. changing the notch size manually in each of the 47 members would have been time consuming using a 2-Dimensional drawing software. An understanding was developed that models created with high levels of precision need cautious planning for tolerance issues. The assembly itself being a multi-directional construct -waffling- makes it even more crucial to plan tolerances and assembly carefully to avoid assembly difficulties. The coming section of the paper extends on the experimental and craft-oriented nature of this research, but on a full-scale artifact, using a different design approach.

**APPLICATION (2): FULL SCALE PAVILION**

The full scale pavilion was an entry to a design competition held inside the department of architecture, designed by a group of undergraduate students. The first author took part as a junior jury member, and afterwards as a participant in the final design development and construction. The students were asked to design a self-assembly modular structure that was easy to assemble and disassemble. The designed pavilion was to be built on campus. The entries varied greatly concerning the design approach, materials used, assembly mechanics and budgets. The winning entry used only Laser cut 6 mm plywood parts with integral joining as will be thoroughly discussed.

The students used a semi-parametric approach for the design of the pavilion, unlike the approach used in designing the first shed. They did not start with a parametric digital model; they started by designing a physical module and then explore the potentials of form generation physically. Parametric modeling was used later to test the effect of solar radiation on the designed surface, and relate the size of panel openings to the amount of radiation falling on each of them. They started by designing 4 different parts: basic solid rhombus, X-shape, straight joint and 18 degree joint (Figure 5).

**Design approach**

Complying with the competition program that demanded a self assembly modular structure within the area of ten squared meters, the team started exploring different morphologies using the basic module designed. The vast array of potentials was an interesting outcome to this modular approach. Laser cut scaled models were used to test formal outcomes as well as constructability and assembly logic (Figure 6).

The team decided to take on this semi-parametric approach as they were newly discovering the potentials of parametric design software, and the time frame given to the design of the competition was not sufficient to start learning. The final design of the pavilion scaled model comprised 972 parts made out of 2 mm medium density fiber (MDF) sheets (Figure 7).

They used Geco plug-in [1] for Grasshopper to simulate the effect of solar radiation on the final designed surface approximation. Afterwards, they related the value of radiation to the offset value between the outer and the inner rhombuses. The higher the value of radiation, the smaller the size of the openings. In order to maintain the modularity requested by the competition program, the team decided to simplify the range of offsets to only three differently sized openings: small, medium and large.

**Full scale testing**

At the full scale fabrication stage, the author was aware that planning the fabrication process needed preparation before coming to the fabrication facility. But it was made a point to leave the design team of undergraduates lead the process, in order to push the limits of experience as far as possible. The design team had to have a clear vision of what, when and
Figure 5
Assembled and exploded module.

Figure 6
Exploring formal outcomes and constructability using scaled physical models.

Figure 7
(Left) 3D visualization of the final design. (Right) 1:10 scaled physical model.
how they want everything to be done. They started preparing the final count of small, medium and large opening rhombuses, X-shapes, straight joints, angled joints. Then they prepared one nested cut sheet with limited number of parts for full scale assembly trials. The prepared parts were tried with different offset values (to account for Laser kerf width) ranging from 0.05 mm to 0.2 mm.

At the fabrication facility, the team started negotiating the aesthetics of the full scale form if the plywood thickness was 4, 6 or 8 mm (Figure 8). After actually cutting some sheets, a decision was made to settle on 6 mm plywood for a number of reasons, the most important of which is the mild stiffness of the cut modules to tolerate bending if pressure is to be applied on the modules during assembly. It is worth noting that 4 mm plywood modules looked aesthetically weak, and sheet bending and imperfections caused the modules not to be completely flat. On the other hand, 8 mm sheets were too thick to accommodate for any bending given the actual size of the rhombus (approximately 30*30 cm).

According to the winning design entry, all the rhombuses and X-shaped modules were to be spray-painted from one side. The straight and angled joints were to be left uncolored. Since the fabrication process had to start as soon as possible, a decision was made to start spray painting right away to give adequate time for the paint to dry. The estimated time for the painting phase was around 3 working days, on the basis of two coats of paint/sheet. At this stage, the team was aware that the high level of precision at which they planned the tolerances of the notches, would be subject to further change. The double coated paint added an extra 0.3mm to the overall thickness of the plywood sheets. Accordingly, a choice was made to fix the notch size in all painted parts, and manipulate the notch size in straight and angled joints only as they were cut directly from unpainted plywood sheets.

**Cutting imperfections and post processing**

One result of the cutting process, was residual thermal effects in a heat-sensitive material e.g. plywood. Sharp-edged cuts are typically produced in non-metal cutting applications. Some thermally sensitive materials exhibit slightly rolled cut-edge surfaces resulting from the thermal effects of the process. During Laser cutting, some of the modules showed different flaws. Defects were mainly related to the edge condition as shown in (Figure 9). Incomplete cutting occurred because the plywood sheets were painted from one side, thus the sheets were subject to planar transformation, something commonly known for craft workers in the field of carpentry. The air suction of the Laser machine responsible for holding the sheet in place during cutting- was not sufficient to completely flatten the sheet, hence the Laser beam did not cut through. On the other hand, paint vaporization was attributed to the heat generated by the first Laser punch- referred to as key-hole by Belforte, (2001)- at the start of the cutting path. Both flaws were easily overcome by post-processing of the modules. The uncut tabs were manually removed by a hand-held cutter, while the paint was refined using a small brush and a touch of paint.
Full scale assembly sequence

After final cutting and sorting, assembly logic was subject to further investigations, using full scale modules. Here, the importance of testing the assembly with a big number of parts was recognized (Figure 10), unlike the first application. In the case of waffling, the profiles were in a multidirectional assembly and dependant on each other causing the parts to warp if the tolerance is not adequate as previously discussed. In this case, the tolerance stack-up did not cause a significant problem, because the parts were in a uni-directional assembly and independent from each other.

Discussions took place concerning all the possibilities of on-situ assembly, given the limitation stated in the competition program to maintain ease of assembly and disassembly. Different strategies (Figure 11) were carefully negotiated to build the pavilion efficiently and within the scheduled time frame.

- **Strategy (A):** Build the whole pavilion in two halves and attach them from the center.
- **Strategy (B):** Build the two straight walls and the vault independently, and place the vault above the vertical walls.
- **Strategy (C):** Build one straight wall and build the vault line-by-line from one side with temporary supports, and then rest on the second straight wall.

In all the previous scenarios, the assembly of either the straight walls or the vault took place in a linear manner, where modules were grouped in rows first and then attached vertically into columns (Figure 13). While strategy (A) was used by the design team to build the final scaled model, it was not by any means applicable in the case of full scale assembly due to the difficulty of handling the two halves. Strategy (C) had a logical sequence but would necessitate using adjustable supports which were not available on campus within the time frame of final assembly. The chosen strategy (B) was also logical as it would only require human muscular force by three groups of participants for handling the three different parts as shown in (Figure 12).

**Final assembly**

The final assembly (Figure 14) of the pavilion comprised 972 parts cut from a total of 33 plywood sheets (152cm*152cm). This number includes all
that the average cutting time each of the final cut-sheets varied from 22 minutes to 30 minutes, depending on the density of the parts nested on each sheet. The modular approach used for the design of the basic modules, rendered numerical coding obsolete. Parts were all identical, only the sequence of assembly was made clear and possible by having the digital model on a laptop screen. The whole pavilion was assembled using muscular force, rubber mallets and a laptop. It consumed a total of 20 working hours on two days, with an average of ten participants.

CONCLUSION

Understanding very precise and inappreciable aspects of digital fabrication not only enhances the knowledge and experience of architects, it goes further towards the redefinition of the whole design to construction process. It can be concluded that understanding the limitations of tools and means of fabrication profoundly informs the digital design and thus reformulates the relation between the architect and the construction site which has been dramatically weakened by conventional practice. Two different design approaches were used in the process of creating the presented applications. Both approaches accounted heavily on the deep understanding of material behavior, tolerance issues, construction logic and finally fabrication tool potentials and limitations. By developing a parametric model designers are not only controlling the fabrication needs but also creating a non-linear workflow that recognizes the importance of how the manufacturing process greatly influences or controls the beginning design phases.

This paper tries to open up the subject and to pinpoint on the importance of craft in the creative digital design and construction endeavors. Digital craft is very similar to legacy craft, where it can be confidently said that creativity is far from conclusive, every day inventive minds are able to take craftsmanship one step further, and along goes digital craft and vice versa.
ACKNOWLEDGMENTS
I would like to sincerely thank the members of the design team who worked fully-hearted to accomplish this artifact: Ahmad Fateen and Rana Hesham (2nd year); Mai Emam, Sara Salama and Zeina Hussein (4th year). This work would have not been possible without the generous sponsorship and help of NOFA Egypt wooden floors factory.

REFERENCES
