Digital to physical: comparative evaluation of three main CNC fabrication technologies adopted for physical modelling in architecture

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DIGITAL TO PHYSICAL

Comparative evaluation of three main CNC fabrication technologies adopted for physical modelling in architecture

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and

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Abstract. Recently, digital fabrication, being a logical extension of computer-aided technology to the material world, was introduced into the field of computational design in architecture. The objective of this experimental study is to investigate and systematise data regarding the production issues and limitations of the main Computer Numerically Controlled (CNC) fabrication technologies adopted for physical modelling in architecture. This study also aims to observe the value of potential feedback to the design process from different types of digitally fabricated architectural models. This experimental research systematically explores digital fabrication as a computer-aided modelling tool, using two international architectural competition projects as case studies: the design of a skyscraper and relocatable schools. Developed by authors especially for this research paper, each case study acts as a test bed to compare and evaluate digital production techniques adopted for physical modelling in architecture. Designs go through a process of refinement using CNC fabrication as an integral part of the design process. Each step in the process is closely evaluated as to its effectiveness according to a matrix of feedback criteria.

Keywords. Design process; digital fabrication; architectural model.

1. Introduction

This paper documents a systematic exploration of the potentials of digital fabrication within the architectural design process. A simple typology of digit-
ally fabricated physical models is applied systematically to two design case studies. The result is a reflection-in-action documentation of the role of materialised virtuality in the architectural design process.

Digital design in architecture progresses as the architectural model progresses. Architects use models as a thinking and defining mechanism for understanding and presenting architectural ideas (Smith 2004, p. vi). With rapid technological development in the field of CNC fabrication, computer-aided design has evolved from pure virtuality to a more complex tool, which blurs the boundary between matter and space (Andia 2001).

2. Physical model typology

Three functional types of physical model were defined for this study: conceptual, working and presentation phases (Arpak 2008).

Conceptual models can be understood as intuitive spatial translations of parameters as varied as the abstract idea. Whilst lacking in physically explicit detail, they can be rich in symbolic content (Downton 2006).

Working models are used as an experimental platform, a tool which informs the design. Working models typically have relatively complex, explicit details of both form and construction (Porter and Neale 2000, p. 21).

Presentation physical models are high-performance instruments for representing final, detailed project solutions in architecture (ibid).

3. Alternative production techniques of digital fabrication

The technology of digital fabrication is rapidly changing. Architects are adopting wide varieties of CNC manufacturing facilities. This materialised virtuality research focuses on three clearly distinct technologies: laser cutting, CNC routing and 3D printing (Kolarevic 2003, p. 31).

4. Case studies

In order to ensure the brief and design goals were independently defined and thus had little influence on the study, two international architectural competition projects were selected as case studies of the application of the three technologies. Physical modelling via digital fabrication was integrated into the design loop at key stages of the project development.

4.1. CASE STUDY AUSTRALIAN FUTURE PROOFING “SCHOOL” (2011)

The conceptual model in this case study explored the spatial relations of two triangular patterns. One of these patterns represented school modules and the other – a canopy system (Figure 1, conceptual model).
In response to the brief requirement for modularity the conceptual digital model was defragmented into basic functional components. The intention of the working design stage was to develop an easy to assemble, relocatable module structure and to explore possible connections and clustering combinations of different types of modules. Scaled prototypes of the main modules were fabricated to test the design solution (Figure 1, working model).

A strategy of separating manufacturing processes was used in order to explore the possibility of fabricating different parts of one virtual model with alternative techniques, and thus engage various materialisation processes to manufacture one single object (Figure 1, presentational model).

4.3. CASE STUDY “TOWER” - EVOLO (2012), SKYSCRAPER COMPETITION

The main objective of the conceptual tower model was to explore formal and spatial qualities of the case, when two different spatial logics interpenetrate into one single volume (Figure 2, conceptual model). Physical models, fabricated for the conceptual stage of this case, revealed the fact that the initial approach of interpenetrating groups of spatial elements was not successful. Tectonic differences between different types of objects (extruded hexagon and boxes) were hardly distinguishable. As a result the design strategy shifted towards surface patterning.

The main objective of the working tower model was to test the formal qualities of the proposed “building skin”. It consisted of a gradual blend of
two symbolic patterns, evaluated according to the level of articulation created by each pattern type (Figure 2, working model).

![Figure 2. Matrix of model: CNC fabricated Tower model.](image)

5. Evaluation criteria

Each digitally fabricated model was evaluated according to key performance criteria for “input – process – output”. The system of criteria was divided into two groups: the first group explored the influence of the technologies on the design process: the interaction or interference between physical and digital models; the second criteria group aimed to evaluate practical issues of CNC fabrication and focused on the following parameters:

- Time spent on digital model preparation, fabrication, and completion (human work / machine work)
- Cost of material and work
- Human contribution to the process of physical model production

The average time spent on model development and the average cost of each type of CNC fabrication technology are documented in Table 1. The following comparison chart shows the proportional time breakdown between human work and digital fabrication.

![Figure 3. Comparison chart (based on experimental data) of model fabrication.](image)
6. Reflection on model fabrication issues and feedback to the initial design

6.1. LASER CUTTING

One of the most distinctive characteristics of laser cutting technology used for physical modelling is that it operates in a two-dimensional spatial framework,

<table>
<thead>
<tr>
<th>LASER CUTTING</th>
<th>Conceptual model</th>
<th>Working model</th>
<th>Presentation model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>School Tower</td>
<td>School Tower</td>
<td>School</td>
</tr>
<tr>
<td>Equipment</td>
<td>Universal Laser systems V-460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre fabrication development</td>
<td>min 180 200</td>
<td>220 320</td>
<td>60</td>
</tr>
<tr>
<td>Laser cutting</td>
<td>min 90 120</td>
<td>120 160</td>
<td>30</td>
</tr>
<tr>
<td>Assembling</td>
<td>min 240 90</td>
<td>280 360</td>
<td>120</td>
</tr>
<tr>
<td>Model dimensions x/y/z</td>
<td>cm 30/12/4</td>
<td>30/25/30</td>
<td>60/25/15</td>
</tr>
<tr>
<td>Cost of material</td>
<td>NZ$ 8 8</td>
<td>16 8</td>
<td>4.5</td>
</tr>
<tr>
<td>Cost of work</td>
<td>NZ$ 15 20</td>
<td>20 25</td>
<td>5</td>
</tr>
<tr>
<td>Total time</td>
<td>min 510 410</td>
<td>620 840</td>
<td>210</td>
</tr>
<tr>
<td>Human work</td>
<td>420 290</td>
<td>500 680</td>
<td>180</td>
</tr>
<tr>
<td>Total cost</td>
<td>NZ$ 23 28</td>
<td>36 33</td>
<td>9.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CNC ROUTING</th>
<th>Modella MDX-40A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre fabrication development</td>
<td>min 10 10</td>
</tr>
<tr>
<td>Setup of material /assembling</td>
<td>min 30 30</td>
</tr>
<tr>
<td>Milling with 6mm drill</td>
<td>min 840 1020</td>
</tr>
<tr>
<td>Model dimensions x/y/z</td>
<td>cm 30/12/4</td>
</tr>
<tr>
<td>Cost of material: “Trimax”</td>
<td>NZ$ 14 16</td>
</tr>
<tr>
<td>Total time</td>
<td>min 840 1060</td>
</tr>
<tr>
<td>Human work</td>
<td>40 40</td>
</tr>
<tr>
<td>Total cost</td>
<td>NZ$ 14 16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3D PRINTING</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre fabrication development/ fixing of rejected model</td>
<td>min 200 40</td>
</tr>
<tr>
<td>3D printing and delivery</td>
<td>NZ$ 19,90 19,90</td>
</tr>
<tr>
<td>Model dimensions x/y/z</td>
<td>cm 10/4/2 9/5/8</td>
</tr>
<tr>
<td>Total time (with delivery)</td>
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</tr>
<tr>
<td>Human work</td>
<td>min 240 360</td>
</tr>
<tr>
<td>Model cost</td>
<td>NZ$ 21,09 31,19</td>
</tr>
<tr>
<td>Total cost</td>
<td>NZ$ 40,99 51,1</td>
</tr>
</tbody>
</table>
while “architects and engineers can aim to design mainly in 3D” (Corser 2010). Two very different strategies for translating a 3D model into a 2D set of elements were identified. One is to interpret a volume as a shell or envelope, subdivided into a set of connected outer surfaces - a logic similar to panelling tools in Rhino (Rhino Tech 2009). This strategy was adopted in the school working model. (Figure 1, working model)

The second strategy was implemented in the Evolo tower’s envelope models (Figure 2, working model). This treats a 3D volume as a solid structure. Here a 3D model is translated into a number of flat sections, outer contours made layer by layer through the volume in a chosen direction. Each fabrication method imposes a rigid mode of thought and a design interpretation that shifts the design from its virtual origin.

The panel approach adopted for the School working model led to its being developed as if it was to be realised onsite for a full scale construction (Figure 1). Design strategies became constrained by the technology to a logic that mirrors production approaches used in the building industry. Laser cutting involved a lot of pre and post fabrication work (Table 1).

6.2. CNC ROUTING

CNC routing has certain limits in terms of precision, material hardness, and particular difficulties in performing undercuts. It is problematic for CNC routers to fabricate sharp inside corners; these will always be filleted by the drill diameter. (Figure 1, 2, details). Parts and details located at a distance less than a drill diameter from each other were merged in the case study models into single volumes. As a result of these production issues, CNC routed models distinctly differed from virtual sources. They were a more abstract and less detailed volumetric translation of the concept than a digital model. These limitations turned out to have certain advantages.

CNC routed conceptual models supplied the most valuable feedback to the initial design. Being to a high degree an abstract and undeveloped representation of the idea, they allowed multiple readings and interpretations, providing a platform for visual formal and creative discoveries. The individual school modules merged when CNC routed, shifting focus from the modules to the whole. In the tower project model observation suggested that envelope patterns should be remodelled in order to emphasise the planned distinctiveness of the two underlying conceptual surface patterns that were to be combined in the tower.
6.3. 3D PRINTING

3D printing technology requirements stated that a virtual model should be converted into a watertight, manifold and less than 1,000,000 polygons mesh. 3D printing requirements also limited minimal wall thickness and detail level (Shapeways 2012). Some of these parameters can be automatically checked and fixed within the majority of modelling software. Unfortunately not all modelling programs have a built-in minimal wall and detail thickness detector. The only option with the modelling software used for this study was to measure all distances manually. This is doable when a model is simple, but as a model gets more developed and complicated, this task seems to be less and less achievable.

The issue of minimum detail level is very important, because the size of the model directly influences its cost (Table 1, cost). As designers reduce model size to achieve affordability, production limitations force simplification and generalising of fine details. The cost of 3D printing directly depends on the amount of material used, so model dimensions not model weight matter. To fabricate larger volumes, solid objects have to be remodelled as thin shell surfaces. This results in additional prefabrication modelling, which even for the experienced user is time-consuming, especially in cases when the model is complex (Table 1, human work).

7. Discussion

The success in these two cases of the integration of digitally fabricated physical models into the iterative design loop of a computer aided design process
(Figure 4) encourages the conclusion that materialised virtuality has a positive contribution to make in digital design. The case study physical models shared exactly the same digital code as their source virtual model, but were realised in the realm of physical reality. Each fabrication technology had its own unique influence on the different stages of a project’s development. In each case it was the manufacturing constraints of the different modes of fabrication that influenced the role of the physical model. For example, for the ideation process, the imprecise CNC routed models were not only effective, but also efficient. The efficiency arose because the models were fabricated with minimal prefabrication development, which led to a fluid and fast ideation process. The roughness and approximation of details of the outcome model was an advantage, because the potential multiple readings of form suggested alternative design solutions (Figure 2).

The laser cut physical model proved to be an efficient modelling tool for the development and improvement of structural design solutions, though it was not yet a ‘total building’ solution” (Burry 2002). The school working model laser cutting pre-fabrication has encouraged the development of the module prototype, which was successfully used for the competition design proposal (Figure 1). The approach adopted for the use of the laser cutting technology stimulated engineering and material-based thinking.

Both CNC routing and 3D printing were successfully used for fabrication of solid volumetric models. Though those technologies allow fabrication of separate elements and parts, they do not necessarily require the development of a detailed structural solution (Figure 2). 3D printing claimed to be a powerful technology, which could accomplish the most precise, developed and complex designs. In practice, it was extremely hard to use 3D printing for elaborated models. The more complex and detailed a model gets, the harder it is to fix mesh issues before printing. The time spent on 3D printing prefabrication dramatically increased when the model was detailed (Table 1, Figure 3). The manufacturing and cost constraints force a choice between a small, very much simplified model or a large and expensive model. At the moment 3D printing is the most expensive technology (Figure 3).

8. Recommendations

During concept design, when form and detail are not fully defined, CNC routing could be an appropriate choice of digital fabrication technology. It requires minimal investment of time, skills and money (Figure 3.).

The large investment of time into pre and post fabrication development of a laser cut physical model was found to carry an added benefit that it can assist in the development of real world structural design solutions.
For all three physical modelling technologies, there is no simple equivalent to the print now button of 2D ‘printing’. Even an experienced CAD user should be prepared to spend a significant amount of time on mesh fixing and thickness checks, especially if the model is complex and detailed. All models in these case studies had to be significantly changed or completely remodelled in order to meet all the requirements of 3D production.

In the 2D world it took some time before the constraints of the printing technologies were incorporated into the virtual world resulting in the What You See Is What You Get (WYSIWYG) representation mode. This paper has shown there are settings from drill bit size in CNC routing to wall thickness in 3D printing which could beneficially be incorporated into virtual modelling software in architecture, as it already is in industrial design. The constraints of model abstraction are less easy to solve ‘in software’ but are no less influential on final design outcomes. The future of this study is best illustrated in the flat panel school and stacked pancake layer tower approaches to the user of laser cut technology. Neither approach is the best. Each hugely influences the design.

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References