SMART ASSEMBLY IN DIGITAL FABRICATION:
DESIGNING WORKFLOW

PAUL LOH\textsuperscript{1}, DAVID LEGGETT\textsuperscript{2} and TIMOTHY CAMERON\textsuperscript{3}
\textsuperscript{1}University of Melbourne, Melbourne, Australia
Paul.loh@unimelb.edu.au
\textsuperscript{2,3}Power to Make, Melbourne, Australia
{david, tim}@llds.com.au

Abstract. Digital fabrication project in academia has produced many grounds for experimentation. In recent years, techniques have also been tested extensively in practice within commercial project setting. This gives rise to an emerging breed of architectural practices whose work is increasingly centred on resolution of complex geometry to realizable projects. The resolution of parametrically driven design to production projects requires a different workflow, as often the compressed timeframe and budget requires the parametric model to cope with multiple streams of construction output as well as utilize the model in concurrent design processes. This paper examines a commercial project as case study to explore the abstraction, reduction and dissemination of information within a digital fabrication workflow. In this project, digital fabrication is deployed to reduce risk; mainly in manufacturing and its lead time. The research reveals how metadesign process at an early stage of the project can contribute to increase efficiency of the parametric model as well as delivering multiple streams of information for all the collaborators: architects, fabricators and builders. The team designed the assembly procedure into the parametric workflow to facilitate off-site and on-site assembly. This is possible through imbedding ‘smart’ detailing and structuring information with the workflow. The paper concludes by reflecting on the workflow and asks if a metadesign driven fabrication workflow can create a more holistic approach to digital fabrication. The outcome of the case study is just one instance of the parametric machine that is developed from an understanding of assembly process. This paper responds to the theme of continuous designing, through looking at digital fabrication as co-emergence of design procedure and practice.

Keywords. Digital fabrication; construction; design workflow.
1. Introduction

Novel technique aside, the primary concern in digital fabrication is the information translation of descriptive geometry to Computer Numerical Control (CNC) fabrication. Scheurer (2010) identified this process as the abstraction of the problem and the reduction of information through removing redundancies. While digital tool making facilitated the procedure (Burry 2011) it is not without its set of difficulties in practice; front loading, deterministic, anticipating flexibility to name a few (Scheurer 2011; Davies 2013).

This paper looks at the digital fabrication of a commercial project as case study, an undulated ceiling for a showroom, to further explore the problem of abstraction, reduction and dissemination of information in practice. The resolution of parametrically driven design to production projects requires a different workflow (Shadkhou and Bignon 2010; Scheurer 2011; Pen de Leon et al 2013), as often the compressed timeframe and budget requires the parametric model to cope with multiple streams of construction output as well as utilize the model in concurrent design processes. In a commercial project, the manufacturing framework is often well defined; that is to say the type of machinery (tools) and material system are implied to reduce the commercial risk of the project, both financially and in manufacturing lead-time. With a prevalence of advanced parametric modelling, this tends to create a situation where the construction method or techniques of a particular project is least developed especially in a commercial project environment. There is neither time nor financial incentive to prototype and develop the material system. Traditionally, architects tend to rely on the builder to resolve the construction and assembly problems. In practice, this poses two issues. Firstly, the design resolution is greater than the construction resolution. The contractor becomes overwhelmed by the complexity and starts pricing in risk to the project (Tower and Bacarini 2012). Secondly, the parametric model becomes representational; an image to build from. The information built into the workflow is descriptive geometry especially in the absence of a physical prototype (Loh 2015).

The team designed a ‘smart’ assembly procedure which allowed the construction sequence to align with the information structure of the parametric model. The ‘smart’ assembly suggested an approach to develop digital fabrication workflow from construction and assembly logic which allowed a more cohesive process from design to fabrication to on site assembly.
2. Background

The project was an undulated timber ceiling for a show suite in Australia, Figure 1. The ceiling consisted of 2,100 battens of Tasmanian Oak each with a 42 x 42mm square profile. The area of the project is about 7m x 7m. The initial design of the ceiling was by Woods Bagot. Power to Make was employed directly by the main contractor, Westbank Constructions, to complete the design and produce fabrication information. At the time of appointment, the design to fabrication team was given a parametric model from the architects sketching the overall form and rough boundary of the ceiling; no further technical resolution was given. The fit-out of the show suite was already half way through the build and the team was given 5 weeks to complete the design (3 weeks for design and 2 weeks for fabrication and installation on site by the contractor) in time for the opening.

This paper will mainly focus on the workflow carried out by Power to Make. Their responsibility included:

- Design and develop the ceiling hanging structure. The hanging structure needed to be flexible enough to avoid the large array of services in the ceiling zone as well as enable a simple and speedy installation procedure.
- A parametric model to allow the architect’s team to fully interact and adjust the design. The survey of the ceiling boundary was not defined at the start of the design process.
- Identify the material quantity so the contractor can confirm final pricing.
• Produce fabrication information for the contractor. Although the contractor used his preferred CNC fabricators, the design team owns and operates a 3-axis CNC router and the tooling knowledge is imbedded in the design.

While the above fits into the context of post-design process (Shadkhou and Bignon 2010) where construction, assembling and fabrication information are assimilated into an integrated digital workflow, the authors argue that there is opportunity for designing through developing construction and assembly strategy as metadesign.

2.1. BUILDING IN SMART ASSEMBLY

The ceiling design consisted of two systems; a standard steel c-channel sub-frame supported by hanging rods forming bays and timber components consisting of vertical timber battens notched at variable heights onto a horizontal batten, typically 4 vertical battens per horizontal batten, refer to Figure 2 below. The steel sub-frame between bays is shared where possible between the timber components of adjacent rows. The timber components are fabricated off-site.

![Figure 2. Assembly sequence of ceiling.](image)

The system is designed to enable the steel sub-frame to be erected on site while the timber components are fabricated off site. When the timber components were completed and delivered to site, the steel hanging structure is ready to receive them. Each piece was indexed so the fabricator and contractor could arrange the components in the correct sequence. The challenge for the design team was to build this assembly sequence into the fabrication process. During the process, the team designed and developed smart assembly detail in response to the various construction and design issues:

• As mentioned, all the fabrication is to be completed by other fabricators. The design team had no control over the fabrication and its assembly procedure.
The contractor was based off site and there was no opportunity to check the parts before delivery to site. Effectively, all the instructions needed to be self-explanatory and indexed on each piece.

- Time constraints on site required components to be quickly erected with a fool-proof assembly sequence to minimize the contractor’s risk. This came down to the detailing of the timber components; to be as simple as possible with minimal amount of steps to reduce labour. The team designed a simple notch within the timber components to facilitate the 3d positioning of the parts. Adding notches to the steel frame was not feasible as it would increase the cost of the package.

- The optimum setting out of the steel sub-frame hanging planes effectively reduced the amount of steel and weight to the entire ceiling. The sub-frame sets out the positioning of all the timber components. As an assembly strategy, it meant that once the first row of timber components is positioned, the spacing of the remaining rows are defined; leaving little room for misalignment as long as each set of timber components are pack tightly, refer to Figure 2, step 3.

From the above, the ‘smartness’ of the design was not in the fabrication process but rather in the assembly sequencing. That is to say, the information of the 3d position of each piece was governed by the assembly sequence or action. The challenge was to develop a workflow that allowed for a concurrent processing of information that mimics the planned sequence. It is worth noting that the geometric complexity of the project was not in the undulated surface but in managing the information flow, from design to fabrication to assembly information.

2.2. BUILDING IN SMART WORKFLOW

The workflow for both design and fabrication visual script was set out in McNeel Rhinoceros with Grasshopper v0.9.0076. The workflow merged the construction logic with the design logic. Construction setting out is declared at stage B of the workflow; tabulated as bays and grids. At stage D, its structure was reorganized to align with the assembly data output. Pen de Leon et al (2013) described the above workflow as Flexible Automated Digital Design to Fabrication Workflow. However there is a key difference; their model excluded or perhaps didn’t prioritise the assembly logic in the workflow.
The above workflow in Figure 3 sketched out the metadesign of the process; designing the design (Giaccardi 2005). The unique positioning of the team within the design and fabrication processes allowed the team to redesign the project from first principle; through construction and/or assembly information (Shadkhou and Bignon 2010). While the construction information described the topology and 3d positioning of the parts, the assembly information described the type of joints or assembly connection; in this case study, the type of notch which enabled precise positioning of the timber components onto the steel sub-frame. What is unique here is the ‘and/or’ possibility of the visual script to process both sets of information in parallel. The team in designing the assembly sequence into the design of the ceiling effectively re-worked the operating system through metadesign process (Giaccardi 2005) in which the visual script plays a larger engagement role in connecting design feedbacks, site survey and site assembly. As a result, the script acted as a coordinated model for the various collaborators; architects, fabricators and builders. This coordinated model allowed the collaborators to close the gap between design, fabrication and assembly. The latter is perhaps the least discussed in research on digital fabrication (Griffith et al 2006; Shadkhou and Bignon 2010) and yet (from the author's experience) construction is one of the least controlled and messy aspects of any fabrication project (Loh 2015).
3. Integrating construction and assembly information

3.1. ALIGNING DATA STRUCTURE WITH CONSTRUCTION SEQUENCE

The visual script is designed to have multiple predetermined output requirements. Firstly, to produce a geometric model with low resolution construction detail for the architects to review, make adjustments and feed back into the workflow. Second, it simultaneously produced a construction model with high resolution construction detail that outputted relevant information to multiple parties: the builder and CNC fabricators. Built into the ceiling components of the construction model was an additional layer of information; instructions for on-site assembly sequence. This layer of assembly sequence required particular information to be included from the outset that allowed for a construction data framework to be setup. The script relied on the flow of information downstream which increased in number of layers as construction information was progressively added to the model. When analyzing workflow of the script, what can be seen as contributing factor to its success was the transfer of the data structure; more precisely, the inheritance of information by each script block whether it was written for design parameter, construction setting out or assembly sequencing. It is the inheritance of the data structure that allowed the continuous workflow and merging of design with construction within the same parametric model.

The team needed to deliver multiple streams of information within a single parametric model. A construction data framework was developed at an early part of the script (stage B). This framework provided two important functions, firstly it provided an opportunity for the script to allow for tolerance in the site conditions to be built in (for example the alignment of existing walls), and secondly initiated the first level of data structure that would be inherited by subsequent scripts. While a seemingly innocuous observation of the data structure, or transfer of data structure, it provided the function for developing the construction and assembly information in parallel. For example in stage B, it showed the ‘Grid’ and ‘Bay’ blocks of the script both inheriting the data structure initiated in the ‘construction data framework’ block. The ‘Grid’ and ‘Bay’ blocks are scripted for both design and construction purpose. While inheriting the same data structure, it demonstrated the development of parallel streams of outputs that exist within the metadesign.

3.2. TRACING THE DATA STRUCTURE

The construction and assembly logic can be observed when tracing the data structure throughout the script. It set out the site constraints and sub-frame
system which led to the conception of the construction data framework; that allowed the design information to be scripted over the top. This was reflected in the construction sequence of the ceiling, for example the first stage of construction involved the installation of steel channels and rods that provided structural support for the timber components.

The ‘Grid’ block (stage B) of the script generated an offset grid that is used to inform the position of vertical battens. The z coordinate of the battens visually represented the geometric resolution of the form as defined by the input surface; the design process. The x and y coordinates which define the grid can be considered as a section of the script owned by the construction process. It is the organizational system for the geometric forms. The regularity of the grid must not be visually interrupted by the structural rationalization of the channels; otherwise the resolution of the surface would be lost. The parallel development of models within the one script allowed for easy negotiation between the design and construction processes. That is to say the structure sub-frame adapted to the geometry of the input surface and vice versa.

Branching out from the ‘grid’ script block (stage B), curves were discretized to represent the input surface and generate the steel channel construction information (stage C). The steel channel information itself had no requirement for the inherited data structure because we only required the length of the members and their datum above the ground. However, it is important that the data structure is inherited by the horizontal battens which rely on the datum of the steel channels and their position to the vertical batten.

The data structure for the horizontal batten saw the convergence of the structural steel channels; the grid and the vertical battens (stage D and E). The horizontal members had to extract pieces of data from each component for a successful outcome; the datum from the structural steel, the location on the grid and the intersection value from the vertical battens for accurate geometric and construction output. It was required to inherit multiple data structures for the information to be passed further downstream and embed into the components in the form of an instructional labelling system.

Stage D, aligning the Data Structure, was a critical and administrative process that collates, aligns, filters and distributes packages of information to the appropriate outputs. Even within the output packages, it was necessary to withhold and release layers of relevant information. Taking the horizontal batten and vertical batten information as an example, both require assembly and construction information to be embedded and have similar information on the first two layers, {Bay; Row…}, however beyond this the required information for each differed. Further positioning information for the timber battens within a row and the addition of notch geometry (this was for posi-
tioning the timber component onto the steel channels) was incorporated while the data structure was converted to labelling text for fabrication. The vertical battens required further positioning information in the form of a letter that indexes the order within the row, refer to Figure 4. Additionally the vertical battens required the output of another piece of information to position the varying locations of notch geometry. This selective distribution of information relied on the correct information layers within the parametric model and the distribution of structured data for appropriate outputs.

Figure 4. Plan showing indexing of components and steel sub-frame.

The above demonstrated that it was useful to introduce a framework based around construction strategy that fitted within the design parameters. It demonstrated flexibility in the parametric workflow which allowed for the production of both geometric and construction models in parallel, each influencing the development of the other. What was less obvious was the continuous input of knowledge and expertise throughout the process between the design team, the fabrication team and the contractor. The layers of information and organization of data are evident of a collaborative and coordinated design and make approach to the project.
4. Conclusion

The above analysis suggests that digital fabrication can be approached from the making perspective; that is, thinking through a set of problems through digital fabrication techniques, CNC tooling and construction strategy. The paper highlighted the potential to narrow the gap between design, fabrication and construction through embedding assembly logic within the design workflow; that is to say, designing from making and not making from a design.

The metadesign process allowed the design team to restructure the ‘operating system’ of the visual script. This was critical in delivering the multiple streams of data within a tight commercial timeframe and budget. It demonstrated the ability of the script to bring together information from different collaborators as well as disseminating the information from an integrated parametric model; a holistic approach to digital fabrication from design to fabrication to construction.

Acknowledgement

The authors would like to acknowledge our collaboration with Woods Bagot and its design team: Eugene Cheah and Su Chen. In addition, we also like to thank Westbank Constructions and Lignum Fine Furniture for seamless integration of the fabrication workflow.

References