Abstract: The design and production of architecture is being heavily influenced by software, both positively and negatively. On the one side, it can be seen to provide new design opportunities while on the other it can create unexpected constraints. It is attractive and easy to generate complex digital forms however to realise it may seem overwhelming. This is reflected in architects constantly developing complex digital forms but they are seldom translated into production. Articles suggest students can work with digital software without much consideration of tolerance for manufacturing, however project and material realities say otherwise. When an appropriate workflow is applied, the making process is not as complicated as many are led to believe. The Gateway Pavilion on Waiheke Island reveals pedagogical requirements to teach students essential skills to produce complex designs with a practical build process. This paper is a case study reviewing the alternate route taken when digital fabrication is no longer an option.

Keywords: Prototyping; design-build; pedagogy.

1. Introduction: the Waiheke Pavilion

The Waiheke Gateway Pavilion was originally conceived in 2009 by an award-winning Architecture practice, Stevens Lawson Architects for the Venice Architecture Biennale. The concept for the pavilion was to be something akin to a dissolving wharenui, a traditional Maori building form that morphs from building to landscape as one moves around the structure. This concept was developed through the implementation of digital tools in design, analysis, and fabrication.

Unitec Institute of technology was tasked to realise the concept design for the Waiheke Headland Sculpture on the Gulf Festival in January 2017. The team consisted of architecture and construction students drawn from first, second, third and fourth year streams. The handful of academic staff and professional consultants to support them were required to negotiate with a large discrepancy in skill between all the students.

It is attractive and easy to generate complex digital or sculptural forms however to realise this, it may seem overwhelming (Sass, 2007). This is reflected in architects constantly developing complex digital
shapes but they are seldom translated into production. Articles suggest students can work with digital software without much consideration of tolerance for manufacturing, however project and material realities say otherwise (Parsons, 2014). The Gateway Pavilion, was a twisting, morphing, spiralling, portal frame-like structure. The intention for both the Biennale and Sculpture trail was to physically realise the scheme through a CNC production methodology, as there were over 300 individual components and over 500 associated unique joints. The structure was built using glulam beams, while the floorboards were specified as treated radiata pine. Each component varied in length from 1100mm to 8000mm that presented a unique engineering and construction challenge to students due to the numerous irregular geometrical connections. The brief for the architecture students was to finalise and detail the design from the provided massing virtual Sketch-Up model, to be subsequently assembled by construction students. The architects, Nicholas Stevens and Gary Lawson, along with the engineering firm Holmes Consulting, encouraged students to collaborate with them as much as possible to work through the developed design process. The timeframe provided was limited, with initial developments taking place from late October 2016 to a complete product in late January 2017. The project was originally designed with low tolerance and high precision making, but a malfunctioning CNC router midway through the project led to a more traditional construction approach to be observed.

The following paper will be divided into four sections. To begin, parameters towards materiality, tolerance, technology, engineering and construction will be discussed in relation to methodology. To follow, a section documents the knowledge gained by producing scaled prototypes to overcome those issues presented in the previous section. To conclude, the pedagogical learning outcomes and project analysis will be discussed.

2. Parameters of Fabricating Objects

This section will investigate the issues that confronted the team of architecture and construction students when developing a construction workflow to create the complex form. The problems that needed to be overcome were:

1. Materiality and Tolerance
2. Technology and software
3. Connections and Joints
4. Analogue Construction Techniques

By investigating these problems, the students devised a method for manufacturing and assembling the Sculpture. However, design and engineering factors were not considered from the Unitec position.

2.1. Materiality and tolerance

With advances in digital fabrication, many believe tolerance can be reduced to zero. Pinpoint precision may be attainable for particular production circumstances, but a thought must be spared to material physics and environmental conditions (Male-Alemony & Portell, 2014) when constructing architecture.

The emblematic work of Walter Gropius and Konrad Wachsmann at the Bauhaus in pre-war Germany prototyped with panelised systems. Their research eventually led to huge benefactors in 1943 at government and at a corporate level to produce large scale factory-based production (Anderson and Anderson, 2007). A four-way connector development was central to the construction system (Smith, 2010), as the panel system alone was not enough to warrant a patent. Gropius and Wachsmann, made
great progress with large amounts of prototyping – the result creating panels that can act as walls, ceilings and floors. In 1947 a factory line was set up to manufacture houses, but failures with production equipment manufacturing suitable tolerances affected output and led the enterprise to bankruptcy (Bergdoll, 2008).

Tolerance needs to be integrated into the design process to realise a successful project (Parsons, 2014). This requires three dimensional virtual models to be prototyped or vetted in order to be constantly updated with construction tolerances and reality’s imperfections become fine-tuned (Willis and Woodward, 2010).

2.2. Technology and software

Modelling conceptual ideas in 3D digital space provides an environment for information to be readily available at the discretion of designers and fabricators fingertips. A great benefit of architectural software, is its ability to create successive design iterations efficiently (Sheil, 2005) Embedded data can be utilized to generate; scaled prototyping, visualisations and quantity surveying information (Iwamoto, 2009). The obvious advantages of working within a digital environment over an analogue hand process is with how information can be manipulated, transferred and replicated with ease (Dunn, 2012). For example, if an architect needed to change a hand drawn design, a workflow to amend it would entail a laborious process to redraw it. Again, if conceptual model was required for spatial validation, a designer cannot simply extract data from a virtual model and print it via a laser cutter. They must be physically measured, drawn, hand cut and checked before any final assembly can be pursued.

Negative impacts of utilising technology can lead to a large quantity of students not being exposed to vital training that is simply eliminated by automation. Questions remain, to what extent can design and construction be democratised (McMeel & Walker, 2015). As the uptake of digital technologies become more prominent with its ease of use, individual skill and expertise of the producer will diminish or be reduced (Parson, 2014). How will future generations of architects cope when the machine fails or simply does not produce what is required without a complete understanding or expertise?

The gap between physical and digital are continuing to converge, it will require the architect or designer to increasingly collaborate or acquire skill, imagination and the expertise of a craftsman. It is likely that prototyping equipment and CNC produced mock-up will become a regular exercise to produce important details as architects become more accustomed to working with Computer Aided Design and Computer Aided manufacture (CAD/CAM) or file to factory workflows (Willis and Woodward, 2010). This process is forcing architects, engineers and builders to need to “throw away the rule book”, and rethink how they approach workflow, the presentation of data and the sharing of ideas (Chaszer and Glymph, 2010).

2.3. Connections and joints

Many prefab innovators try to draw parallels to flat pack furniture or Lego, Meccano, and other children’s assembly toys. Connector joints are key for a successful product. Sass notes that snap-fit mechanical joints - dovetails, slots, and tabs - are common and are the most appropriate method for aligning and assembling building components. One must recognise that assembly and attachment control is part of the design process. A designer must judge factors of functionality, component shape, locking, assembly motion, tolerance, and strength prior to manufacturing (Sass, 2007). Therefore, it can be safe to say the design process must include prototyping and testing to some extent.
2.4. Analogue construction

There is a need for contractors to not only be familiar with CAD/CAM capability, but also be well equipped with conventional construction knowledge and skill to cope with challenges that cannot be anticipated in a computer-generated model. Designers need to be well versed in fabrication logic to not only be able to produce tangible digital production files, but also a range of well-produced 2D drawings to service large portion of contractors who are not well versed in the 3D realm. The fact remains that even when armed with digital technologies, complex design requires large amounts of skill and expertise (Chaszer and Glymph, 2010).

It is a known fact that analogue construction methods cannot produce the same levels of accuracy as if it was produced digitally. However, when an appropriate workflow is applied, the making process is not as complicated as many are led to believe (Krygiel, 2010).

Responsibility with analogue fabrication of components rests with a larger sum of people, when compared with automated fabrication. The draftsperson needs to draw information that can be easily comprehended and the fabricator needs to measure. A digital workflow by comparison only requires an optimal team to produce digital file for fabrication. The requirement for organisation is much less and simpler with files only needing to be decided by software, therefore the requirement creating time-consuming elements such as a well-documented set of shop drawings is negated (Sass, 2007).

2.5. Methodology

Complex digital forms can be easily produced in a digital environment, however to realize them in a physical world, it may seem overwhelming when the incorrect approach informs production (Sass, 2007). The creation of the gateway pavilion needed to have a flexible, but rigorous approach to cope with the limited timeframe provided. The design process, a fundamental staple within an architectural practice is not so dissimilar to the iterative process within a science experiment to resolve problems (Lucas, 2016). There is a need for architects to work with, engineers and other construction consultants to break down design ideas into manageable portions. This produces numerous scenarios to be tested allowing for fewer uncertainties to arise (Anderson and Anderson, 2006). If you can test the design before committing it to the contractual process, you can afford to be more ambitious. Although, it must be recognized that there is rarely enough time for major changes to be implemented into an idea (Thornton, 2005). An iterative prototyping programme therefore was selected to develop the design into a credible construction system by observing and researching how others have integrated different scales of prototyping into the production programme (Stacey, 2008).

3. Prototyping Process

The prototyping process was an essential stage of the project to make the construction process proceed smoothly. The practise of prototyping allowed the students to formulate solutions and an understanding of materials and unfamiliar construction methods. Every decision from scale, shape and placement on site, through to construction details were decided through the creation of prototypes.

The following section will firstly explain why the learning from prototyping through digital methods did not go to waste once the CNC machine became inoperable. Secondly, a justification on why it was required to test an alternative method of fabrication before continuing to site will be discusses. To conclude, an analysis will describe the knowledge gained from testing with prototypes.
3.1. Digital prototyping

The original workflow developed for this project worked between creating digital virtual models and producing scaled mock up models. The first mock up model was created at 1:10 for several reasons. The first was to assess the scale and size, the second, to provide visual representation to all the shareholders in the project, and lastly to refine elements of the sculptural form that looked out of place. The design team, which consisted of engineers, architects, students and academic staff, referenced this model throughout the design and fabrication stages. It was much easier to negotiate discourse around a large comprehensive model to resolve issues. For example, the problem involving the alignment of how each component would meet was noticed at this point and allowed the design team to re-evaluate the digital model. An even more trivial problem of understanding that the structure was not simply a series of portals, but rather a spiralling reciprocal structure was only noticed by many through viewing the physical model.

Throughout the project the conflict between architecture and engineering was discovered and resolved by the production of this model. Specifically, it was to the placement of the bracing elements, metal rods that worked in both compression and tension to stiffen the overall structure and equally space the spiral components apart. Compromise had to be made between architect and engineer, with the architect pushing for a seamless line of frame spacing, while the engineer must ensure the effectiveness of the spacing.

Digital analysis was utilized by the engineer to check spacer connections between each of the portal sections. This structural analysis was done through using a Grasshopper script, a Rhinoceros 3D plugin, which identified the number of spacers that are incorrectly placed. The script began by 3D model inputs being assigned to various groups based on which spacer rule is associated with it. A rule is then applied with intersecting and non-intersecting results appearing as true or false. The data trees were consequently split in relation to these results and therefore identified correct and incorrect spacers. This structural analysis meant that issues could be fixed on the 3D model and be adjusted in the shop drawings while also reducing the amount of back and forth consulting between the engineer and architect.

![Grasshopper script used to check connections.](image)

The next prototype to be developed as the digitally produced 1:1 detailed section that investigated the specification of products other than the glulam and the connection details. Time constraints did not allow for procurement of glulam beams for testing purposes, consequently forcing the team to select Laminated Veneer Lumber (LVL) as suitable replacements.

Firstly, the digital model that was created for this prototype allowed for the quantity surveying to take place. Secondly, the prototype also enabled the students to understand how thick pieces of timber can be cut without straining machinery and consequently damaging the material. Lastly the finer details with
connections was resolved at this point. It was found that the threaded rod had to be cut professionally offsite with the correct machinery and the stainless-steel tube was insufficiently specified leading to further changes being made. Even though the digital model accounted for some tolerance, the students concluded that it needed to increase, leading to larger holes to be bored and the requirement for the bolts to be longer.

![Figure 2 (Left): 1:10 Prototype showing overall form and assembly method; Figure 3 (Right): 1:1 Portal section prototype testing manufacturing and connection](image)

### 3.2. Analogue prototyping of six spiralling portal frames

When the malfunction in the CNC was discovered, production of the components was already in motion. Due to the change in circumstances, another full-scale prototype was implemented to test assembly of the first six spiralling portal frames and how the project could be produced without automation.

Previously to this phase, the majority of developments undertaken was by the architecture students and respective design consultants. The manufacture and testing of the final prototype, along with eventual production of components, signalled a shift in workflow as construction students were introduced to the project to provide much needed support. Construction students and some building consultants were initially hesitant to interact with a new form of communication beyond the traditional drawing and to accept digital processes in conjunction with prototyping. Experience on their part dictated their opinion, which by all means is valid as local building practice does not generally get the opportunity to prototype or build complex architectural forms (Krygiel, 2012). As the design programme progressed, acceptance and an understanding towards the need for such an approach developed.

It was important that the drawings were accurate, as it played a crucial part in the manufacturing process. The need for diagrams to aid in the visualisation for projects and their realisation is key to disseminate information for fabrication (Allen, 2009). This concept is highlighted within the prototyping phases, as the original shop drawings needed to be heavily augmented to ensure the communication with entry level labour was understood. The fastest form of prototyping is not by creating mock up or digital simulations, but by augmenting, developing and drawing over by hand and pencil (Gage, 2012). Once drawings were completed the responsibility was handed over to the team members who are responsible for marking out cut lines and cutting the material. In the marking-out process, repetition of similar tasks
meant a lapse in concentration and human error was more likely to occur than if an automated process was used. A solution came from constant reference to the computer model, coordinating one another into manageable organisational teams and the importance of documentation tracking systems to ensure mistakes would not occur.

This prototyping stage was by far the most important as it highlighted problems in material lengths, the documentation and the assembly process. The architectural students formulated a solution to repurpose and expand on the vector CAD/CAM files to produce highly detailed shop drawings. The drawing requirements increased in this prototyping stage to over 600 pages more than double the original amount. When the CAD/CAM files were produced it did not need measurements to be represented for CNC production. Print paper documentation, however needed to be legible by the human eye. The first iteration of the shop drawings were only printed on a single sheet of paper and described components with a confusing amount of information. To overcome this, it was found that each two or more schematic drawings to represent each individual component. Other changes in the documentation can be partly due to how the original components were designed with small tolerance and automated production in mind. As a result, the new prototype showed that this allowance would not work due to unexpected movement in the frame and poorly aligned cuts in the handmade fabricated process. Fortunately the assembly of the structure had already been predetermined to be completed by hand, this allowed for much of the assembly documentation to remain the same.

The constant change of hands associated with analogue construction meant that a strong method of communication was needed. At first, the group of students found it difficult, but over time common ground was found through the prototyping process. To achieve this, it led to the architecture students acquiring an understanding of fabrication and assembly techniques in order to negotiate material and detailing. The construction students on the other hand, decided to contribute to the design process through accepting that planning, documentation and iterative prototyping can lead to a well resolved product, and assisting in the repetitive tasks required to realise the final structure.

Figures 4 and 5: Prototyping of 6 spiralling portal frames
4. Conclusion

Though the Waiheke Gateway Pavilion is of a calibre targeted towards automated and expert joiners with expensive production operations, students were able to effectively engage in the development and realization of the project through following systematic processes. The students’, determination to implement what they learnt throughout the prototyping stages assisted them to take part effectively with the project. While for the organisers, developing strategies to best inform, instruct and distribute labour led to the success of the final outcome for the project on Waiheke Island.

4.1. Pedagogical learning

The need to create the appropriate workspace for students is essential for a good workflow, as it enhances the student’s enthusiasm for making and allows them to connect their own digital models to small scale prototypes (Burgess, 2015). The environment allowed essential skills and values of craft to be incorporate into the design process. The project was very temperamental, with frequently changing deadlines making outcomes unpredictable and adding pressure to the students. To overcome this, students were encouraged to be involved in the all the possible tasks from programming timelines to ordering material and in turn allowed for confidence in individual ability to grow. Throughout the project select students were kept up to date with the key deadlines and changes.

The notion of designers as builders (Kieran and Timberlake, 2004) is demonstrated in this project by the architecture students contributing to aspects such as quality assurance, quantity surveying, fabrication, and assembly phases of the project. This was necessary in order to overcome problems that arose due to workflow changes. Few designers utilise craft themselves to create things. Perhaps they do not have the opportunity, or lack of skill. Perhaps there is a cultural stigma where making things in the broadest sense is not valued, and physical craft less so. If designers had to physically work onsite they would appreciate the difficulty of some the tasks they expect others to do (Thornton, 2005).

4.2. Analysis

When combining the available digital tools for communication and design development with an analogue fabrication technique, the Waiheke Gateway Pavilion developed an integrated design and build strategy. This blend of two traditionally opposing methods made for the success of the complex spiralling structure. This project highlights the value of employing iterative processes and how having an integrated workflow can achieve a successful outcome. Iterative investigation was first required to investigate the most efficient approach to develop an alternative fabrication process. Prototyping throughout this project allowed for further understanding of how corner joints and detailed information was to be assembled at full scale.

It became evident that for this project to be successful a greater understanding of other available construction processes needed to be explored comprehensively through prototyping at different scales. Throughout the prototyping process constant design analysis was required by all members of the design and build teams. Students found the process of prototyping to be beneficial to break down and comprehend the project into manageable sections. The practise of prototyping allowed the students to formulate solutions to problems. The assumption that students brought with them various skills sets allowed for a workflow to be tailored and organised not only for efficient outputs, but to ensure the students gained understanding, experience and knowledge for future projects. The architecture students gained an understanding of how materials can contribute to design outputs, and in turn provided them
with different outlook in how to approach digitally designed outcomes. This combination of perspectives from different disciplines allowed for experimentation to develop and to test new strategies.

Important learning experiences came with re-evaluating the project due to the need for analogue organisation; new skills and knowledge to be understood, acquired, and to be worked back into the design to fabrication process. Aspects on how best to integrate students from collaborating industries that tend to have conflicting purposes between the importances of design and the practicable needed to be negotiated. Overall this project was a learning experience not only for the architectural students that were involved from the designing and documentation stages, but also for the construction students that only joined in fabrication stages of the project. New skill levels have been achieved for the architecture students as they can now not only produce encoded data for digital production and a highly-defined computer generated model, but can also create shop drawings that convey accurate information for the construction trades. In addition, the project has highlighted the value of bringing closer the disciplines of design and construction to encourage more collaborative working arrangements greatly benefiting the final result.

Figure 6: Interior shot of final construction on opening day of Headland Sculpture on the Gulf festival.

Acknowledgements

Special thanks to the following people involved in the project from students to industry professionals; Adrian Janus, Rohini Contractor, Sebastian Siggaard, Carl Salas, Laura Stephenson, Ernest Aurora, Elizabeth Westerlund, Siitia Siitia, John Tuilua, Luke Soares, Jerome Ramsay, Anton Lee-Katia, Glenna Taulilo-Makea, Kelpie McKenna, Adam Roberts, Fritz Gabriel, Miguel Widdison, Kyle Tagumasi, Stephanie Wade, Peter McPherson, Yusef Patel, Richard Mcllroy, Renee Davis, Bruce Hilliard, Bill Dobbin, Simon Renton, Duncan Elliot, Nicholas Stevens, Gary Lawson, Matthew Harwood, and Hamish Nevile.

The Waiheke Pavilion would not be possible without the support of Steven Lawsons Architects, Ebert Construction, Holmes Consulting and Unitec Institute of Technology.
References


