The DigiShed: a small structure designed, fabricated and assembled with three emergent digital technologies

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Abstract: Since 2010 the University of Tasmania, Architecture & Design has fabricated structures using a custom sheet-based digital fabrication construction system. This paper highlights how present and emergent digital technologies have been applied to the design, fabrication and assembly of a small experimental structure known as the DigiShed. The DigiShed has been designed to optimise the characteristics of wood-based sheet products processed with CNC-driven digital fabrication. An analytic comparison is made with an equivalent lightweight timber framed structure. Augmented Reality has been used to communicate each component’s physical location within the structure and the overall assembly sequence. The assembled DigiShed has subsequently been used as a canvas for students to investigate design parameters for a cladding system using Incremental Sheet Forming (ISF), a process where a robot arm deforms a flat metal sheet into a three-dimensional form. The paper speculates how the results of the research might be applied to larger and more complex structures.

Keywords: digital fabrication; monocoque construction; incremental sheet forming; augmented reality.

1. INTRODUCTION

The University of Tasmania, Architecture & Design has extensive experience of integrating an experiential teaching philosophy based around ‘making’ with research activities focused on digital technologies (Burnham and Wallis, 2012). The paper will describe how a small experimental structure, known as the DigiShed, has been used to analyse a digital fabrication construction system known as FabTab™, experiment with augmented reality (AR) in supporting manual component assembly, and the use of Incremental Sheet Forming (ISF) to fabricate cladding panels.

The research has been undertaken by lecturers and students in an Advanced Design Research unit in the Masters of Architecture. This unit encourages students to conduct research aligned with one or more of the methodologies defined by Frayling: ‘research into design’, ‘research through design’, and ‘research for design’ (Frayling, 1993). The research activities described here are focused on ‘research through design’, within which, Frayling describes three approaches: materials research, development work and action research. Development work, Frayling suggests, may include, “customising a piece of technology to do something no-one had considered before and communicating the results.” Action research is, “where a research diary tells in a step-by-step way, of a practical experiment in the studios, and the resulting report aims to contextualise it.” Students have undertaken literature reviews and primary research activities in order to establish critical analytic and design parameters.
1.1 The TradShed

In first year Building Technology in Design units students build small sheds in order to develop a tangible understanding of lightweight timber frame construction compliant to Australian Standard 1684.2 (Council of Standards, 2010). The sheds are wrapped with a breather membrane, lined, insulated and clad. The completed sheds are subsequently used by students to test a hypothesis of their choosing relating to thermal performance. The Tradsheds, as they will be called in this paper, thus play an important role in introducing principles of building technology and thermal performance (Figure 1).

![Figure 1: TradShed: framing; isometric, insulaed and wrapped; clad in batten/board hardwood.]

1.2 ‘FabTab™ and Socially Productive Applications of Digital Fabrication

Since 2010 digital fabrication has been integrated into making activities, primarily through the use of a custom sheet-based digital fabrication construction system (Tubby et al., 2012). FabTab™ is the outcome of project-based research, community focused practice, design studio teaching, and collaborations with industry and community partners. FabTab™ comprises a three-dimensional arrangement of CNC cut plywood components, connected with multiple tab and slot joints (MTSJ) and assembled with rubber mallets and screws. The development of FabTab™ was influenced by work conducted by Shigeru Ban Associates (2010), Sass and Botha (2006), Wikihouse (2012) and Facit Homes (Johnson, 2014). Designs are developed using a custom Sketchup plugin.

FabTab is a semi-monocoque construction, taking advantage of the characteristics of a rigid, structurally certified, dimensionally stable sheet material, primarily 12mm CD structural plywood. Three basic approaches to semi-monocoque construction can be seen in the projects to date: firstly, the stiffeners are internal, serving as fixed furniture on the interior (Figure 2a); secondly the stiffeners are external, providing a cavity for insulation (Figure 2b); thirdly, the stiffeners are internal and external, providing both furniture internally and a cavity for insulation externally (Figure 2c).

![Figure 2a,b and c: Castle 5, Castle X and Scout-hut examples of semi-monocoque construction system.]

A core and enduring motivation for the development of FabTab™ has been to allow people with limited building experience to assemble habitable structures with basic hand--tools. FabTab™ has been applied in several socially productive projects which have provided formal construction training for unemployed youth. The Castle, a collaboration with a local Youth Shelter, has deployed autonomous micro-dwellings to the backyards of households in need of additional space (Burnham and Green, 2011). Castles have been purchased by Housing Tasmania as part of their Affordable Housing Action Plan. In 2016 six flat-packed kits (each comprising 612 components) were shipped to Scouts Western Australia where the Scouthuts have been assembled by Youth Justice Program participants. These projects have demonstrated that dimensionally precise components, arranged within structurally and spatially defined parameters, can provide an empowering and accessible building experience.
1.3 The DigiShed

The motivations for the design of the DigiShed were twofold: to expose students to a contemporary construction system and to extend FabTab™ research in preparation for a larger and more complex commercial project. The DigiShed is a digitally fabricated equivalent of the TradShed, rather than an identical replica. The DigiShed, comprised of 67 components, responds to the opportunities of digital fabrication and the inherent characteristics of plywood; an expression of its underlying philosophy and the resulting logic (Figure 3). The factors influencing the design of the DigiShed are:

- External dimensions relate to the maximum a CNC router can cut from a standard sheet.
- Curved profile responds to simplicity in junction detailing and to Bushfire Attack Level (BAL).
- Configuration of cavity stiffeners complies with structural wind-loading requirements.
- External plywood skin to reduce roof depth and facilitate alternative cladding options.
- Cavity depth facilitates R3.0 insulation throughout the envelope.
- Floor construction comprised of an interlocking two-way grillage structure.

![Figure 3: DigiShed assembly sequence, floor assembly and completed structure.](image)

2. COMPARATIVE ANALYSIS OF THE DIGISHED AND TRADSHEED

The comparative analysis was undertaken in order to quantify the implications - material, structural, thermal, buildability and cost-benefit - of two radically different construction systems. Two versions of the DigiShed will be analysed; one including an outer skin of plywood (as built) referred to as DigiShed 2 and one with only an inner skin of plywood referred to DigiShed 1.

2.1 Characteristics and Specifications

The characteristics (Table 1) and comparison of the sheds (Table 2) are shown below.

<table>
<thead>
<tr>
<th>Table 1: Characteristics of the Tradshed and DigiShed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TradShed</strong></td>
</tr>
<tr>
<td>Internal lining</td>
</tr>
<tr>
<td>Structure</td>
</tr>
<tr>
<td>Insulation</td>
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<tr>
<td>Breather Membrane</td>
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<tr>
<td>Cladding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DigiShed (2 skins)</th>
<th>Components fabricated using CNC router (35mm screw fixing throughout)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal lining</td>
<td>12 mm CD Plywood</td>
</tr>
<tr>
<td>Structure</td>
<td>12 mm CD Plywood</td>
</tr>
<tr>
<td>Insulation</td>
<td>R3.0 Fibreglass Batts</td>
</tr>
<tr>
<td>External sheathing</td>
<td>12 mm CD Plywood</td>
</tr>
<tr>
<td>Breather Membrane</td>
<td></td>
</tr>
<tr>
<td>Cladding</td>
<td>Colorbond Custom Orb</td>
</tr>
</tbody>
</table>
Table 2: Comparison of the Tradshed and DigiShed

<table>
<thead>
<tr>
<th></th>
<th>External dimensions (l, w, h)</th>
<th>Internal Volume m³</th>
<th>Material Volume m³</th>
<th>Mass kg</th>
<th>Material wastage %</th>
<th>Embodied Energy MJ</th>
<th>Cost $ Materials;</th>
</tr>
</thead>
<tbody>
<tr>
<td>TradShed</td>
<td>2400; 2390; 3000</td>
<td>7.84</td>
<td>0.32</td>
<td>250</td>
<td>10%</td>
<td>1020</td>
<td>967; 3185</td>
</tr>
<tr>
<td>DigiShed (2 skins)</td>
<td>2200; 2100; 3080</td>
<td>8.12</td>
<td>0.864</td>
<td>475</td>
<td>12%</td>
<td>4940</td>
<td>1602; 3550</td>
</tr>
<tr>
<td>DigiShed (1 skin)</td>
<td>As Above</td>
<td>As above</td>
<td>0.656</td>
<td>342</td>
<td>15%</td>
<td>3556</td>
<td>1192; 2550</td>
</tr>
</tbody>
</table>

2.2 Embodied Energy

Process Energy Requirement (PER) measures the amount of energy required to manufacture a material. Kiln Dried soft wood has a PER of 3.4 MJ/kg, plywood 10.4 MJ/KG and plasterboard 4.4 MJ/KG (Department of Environment and Energy, 2018). Plywood production involves energy intense processes including peeling, drying, gluing, pressing, cutting and sanding of the sheets. The DigiShed (double skin) embodies around 5 times the amount of energy in the Tradshed and the DigiShed (single skin) embodies 3.5 times the amount of energy in the Tradshed. These figures include waste material.

2.3 Structural Characteristics

The structural characteristics of Australian Standard AS1684.2 are embodied in the TradShed, a skin-on-frame system. Solid timber rafters, wall studs and floor joists transfer static and dynamic loads through the structure to the foundations. Steel strapping is used for lateral bracing and to provide hold-down. While a detailed structural analysis of FabTab™ has not yet been completed, advice and guidance has been by a consulting engineer in terms of overall characteristics and specific parameters.

The DigiShed is a semi-monocoque construction system - used widely in aircraft, boat and car manufacture - where loads are largely transferred to the floor through the skin (Hassan M.P., 2012). There is no independent structural frame or strapping. The floor of the DigiShed is composed of two skins of plywood separated by an interlocking grillage. The inner and outer skins are separated by ‘spacer’ components. A significant advantage of semi-monocoque construction is that the skin, as well as transferring loads, also encloses space. This approach differs from many other sheet-based digitally fabricated building systems where solid timber framing elements are essentially replaced with CNC cut plywood frames (Sass and Botha, 2006; Wikihouse, 2012).

The TradShed requires either steel strapping or plywood sheathing to provide adequate bracing. The DigiShed is inherently braced by the plywood skin(s). There is a significant difference in bracing strength, between strap bracing (3kN/m) and 12mm plywood (6-8.7kN/m). DigiShed 2 has more than 3.5 times the amount of bracing required for N4 wind category and more than 5.5 times that required for N3. Digished 1 had 3-5kN/m more than what is required for N4 wind classification. Using the strongest speed bracing method available the TradShed would be compliant for an N3 rating. The grillage floor structure has been load tested and achieved a rating of approximately 4.5Kpa (441kg/m²).

Connections between all DigiShed components involves Multiple Tab Slot Jointing (MTSJ) for perpendicular connections and what we have termed ‘supported dovetail’ jointing (incorporating a slot and tab joint within the dovetail pattern) for planar connections. Shear and upload testing of these connections is on-going and the results will be compared with AS1684.2 strapping.

2.4 Material Wastage

Material wastage involved in the fabrication of the sheds has been calculated as a percentage of materials supplied. For the TradShed waste material was collected after docking of the framing material and was estimated to be 15%. DigiShed wastage is a result of component nesting efficiency, which is in turn a factor of component shape and dimension. For DigiShed 2 wastage is around 21.5%, based on a ratio of component area (63.32m²) to the area of the 28 sheets of plywood used (80.64m²).

2.5 Condensation

The wall constructions of both sheds, have been modelled with JPA Designer dewpoint calculation software, based on conditions in Launceston, Tasmania. The internal temperature has been modelled at 17°C with a relative humidity of 60%, based on one or two occupants. Modelling for the TradShed indicates that in a worst-case scenario (low temperatures and high humidity) moisture in the air condensates between the breather membrane and the cladding, allowing moisture to either evaporate or run down the cavity to the ground. In a worst-case scenario Modelling for the DigiShed indicates that the dewpoint would fall within the external plywood skin, suggesting that condensation could potentially lead to mould
and structural damage. Removing the external plywood skin removes the risk of interstitial condensation and the wall construction behaves similarly to the TradShed.

2.6 Cost Benefit Analysis

The materials consumed by the DigiShed 2 and DigiShed 1 cost 66% and 23% respectively more than the Tradshed. Costs for labour have been based on our experience of CNC operation and assembly by low-skilled labour for the DigiShed, and on Rawlinsons Construction Cost Guide (2012) for the TradShed. The Digished 2 labour costs were 11% more than the Tradshed, and DigiShed 1 labour costs were 20% less than the TradShed. The total construction costs (including both materials and labour) are as follows: TradShed $4152, DigiShed 2 $5152 and the DigiShed 1 $3752. The implication of this comparison is that TasFab™ construction is competitive with 1684.2 construction.

2.7 Implications for Future Applications

The comparative analysis has led to changes in recent applications of FabTab™. Firstly, the outer plywood skin has been removed due to concerns over the apparent susceptibility to damage from condensation. This change results in an overall reduction in material and labour costs, although the roof structure needs to be slightly deepened to compensate for the loss of the second skin. The second change has been to further optimise sheet usage, resulting in changes to component designs. Subsequent redesign of components has reduced waste to around 15%. Cutting two sets of DigiShed components from the same file reduces the waste 12%, suggesting that larger structures result in improved material efficiency.

3. AUGMENTED REALITY GUIDED MANUAL ASSEMBLY

Efficient component identification, location and sequencing are necessary to reduce assembly time and to avoid frustrations associated with sequencing errors. Visual identification of components is currently achieved by a reference code cut into the surface of the plywood. Component sequencing, placement and orientation is currently communicated with an animated video where each component is highlighted in sequence and notes included where required (Figure 4). Feedback from assembly teams has been positive, with a strong preference for the animation over previous paper-based ‘step-by-step’ instructions.

3.1 Augmented Reality

Originally conceived in 1968 by Ivan Sutherland (Arth et al., 2015), Augmented Reality (AR), communicates three-dimensional design information in the form of a hologram accessed through a device such as the Microsoft Hololens. Whereas Virtual Reality (VR) immerses the participants completely within a digital environment AR differs in that both the real environment and virtual are merged (Milovanvic et al., 2017). AR requires less processing than VR but more sophisticated registration. It has been demonstrated that AR when integrated into Building Information Modelling (BIM), can be commercially viable and communicate a better spatial sense to clients (Oesterreich et al., 2017). Most of the focus of AR research to date has been on the design phase, but several authors have demonstrated that AR can guide building or assembly procedures (Yuan et al., 2008; Reiners et al., 1998) by superimposing virtual component position, location and sequencing over the real assembly environment.

3.2 AR guided manual assembly workflow

A collaboration with Fologram - a team of architectural designers and technology innovators - has inspired the development of an AR guided workflow for building assembly. The Sketchup model is exported into Rhino and processed through a
Grasshopper script. A dynamic hologram of the DigiShed structure is projected within the Hololens, at either full size or any desired scale. The full-size hologram can be registered precisely to the real assembly environment, ensuring that the position and orientation of every virtual component can be matched by the position and orientation of the corresponding real component. An array of virtual ‘buttons’, each tagged with a component reference code, are located adjacent to the DigiShed hologram (see Figure 4). Selecting a button with the appropriate finger gesture highlights the component in the virtual model, enabling participants to locate each component within the structure.

3.3 Analysis and speculation

The experience of using AR guided manual assembly on the DigiShed suggests several advantages over previous methods, some potential refinements as well as some practical concerns. Most significant is the ability for the participants to observe and experience the completed structure, at any scale, and from any viewpoint. Observing the relationship between all building systems (eg. structure, battens, cladding, services etc.), by switching on and off layers in the virtual model enables participants to predict assembly steps beyond the immediate task, identifying potential conflicts. Matching the progress of the physical assembly with the hologram contributes to a positive ‘poka yoke’, drawing attention to errors as they occur. Matching the location and orientation of the virtual and real reference codes is particularly helpful. An animated assembly video does not provide such recognisable feedback when an error is occurring. More generally the ability for all participants - whether designers, fabricators, clients or evaluators - to be in the same ‘space’ suggests that professional or cultural bias could be reduced.

Component sequencing is not embedded in the current Fologram program. A visual ordering of the buttons (eg. from left to right) would be possible but would not prevent errors. Sequencing could be incorporated into a step-by-step animated playback mode, sequentially adding components in the correct order. A troublesome aspect of the experience was the repeated removal of the headset, required in order to focus on the physical attachment of each component. Headset removal could also result in involuntary changes to software or hardware settings. More broadly the use of AR guided manual assembly raises significant question around design and construction documentation. If a design is documented digitally in three-dimensions and construction documentation is provided digitally in three-dimensions then two-dimensional documentation appears to become an abstract irrelevance.

4. DIGITALLY FABRICATED CLADDING UNITS

The curved, seamless profile of the DigiShed, designed to avoid detailing weaknesses that typically occur at orthogonal junctions, suggests an approach to cladding entirely different to the batten-on-board Tradshed cladding. A group of Masters of Architecture students were assigned the task of designing and fabricating a low-cost metallic cladding system for the DigiShed using Incremental Sheet Forming (ISF). The task would include primary research, identifying relevant variables inherent to ISF forming and the selected material, as well the development of patterning that satisfied both functional and creative ends.

4.1 Fundamental Principles

ISF is a process by which sheet-metal is incrementally deformed using a numerically controlled machine in order to produce complex 3D geometries. Geometries generated by CAD software are translated into a tool-path based on a series of contours. The three-dimensional form is created by the ball nose tool pressing onto the material - the Kuka robot applies a force of 130kg - as it moves along the toolpath, gradually stepping down for each contour (Alves de Sousa, 2016). The advantage of ISF, compared to other sheet-metal forming processes, is that a single tool can produce a variety of forms without a die. The implication is that geometries can be generated and manufactured efficiently (Figure 5).

Figure 5: ISF: spherical head tool; primary research; prototype tile; texture of final cladding panel
4.2 Establishing Parameters for Initial Testing

A literature review, in conjunction with preliminary testing to develop confidence and proficiency in file transfer and production set-up, led to the following criteria being established for tile prototyping.

- The tool - a 23mm diameter spherical head - balances the need to reduce friction (Lu, B. et al., 2014) while still being capable of producing detailed patterning.
- The material - 1.2mm aluminium sheet - is relatively low-cost and achieves a good balance between formability, thickness and hardness (Baily, D. et al., 2014; Nicholas, P. et al., 2016).
- The ‘step-down’ between each contour - 0.5mm - selected for accuracy between geometries and smooth surface (Hamedon, Z. et al., 2018).
- Vegetable oil selected as the preferred lubrication based on friction reduction and being a natural product (Weickowski, K., 2017).
- The tile size - 260x260mm - achieves a balance between reducing deflection while being sufficient to incorporate patterns and forms.
- A feed rate of 700mm/minute achieves a balance between surface finish, speed, wall angles and formability (Hamedon, Z. et al., 2018).

Despite best efforts to ensure consistent conditions for the forming process observations suggested that outcomes could not be assumed to always be replicated. The following ‘rules of thumb’ were observed.

- An exponential relationship between wall angle and probability of failure.
- The resistance of the tile to bending increases with the depth of the form.
- Maximum formability has a stronger relationship to the area being formed than to the wall angle.
- Proximity to perimeter support increases the sharpness of forming but increases risk of failure.
- Deformation of the sheet under pressure led to the profiles differing based on location.
- Feed rate, lubricant and step-down were all found to be effective in producing a smooth surface.

4.3 Patterning, Deformation and Tile Connections

The initial testing resulted in the selection of a ‘dimple’ pattern (Figure 3) as the most effective in terms of strength and reliable forming. The distribution of dimples across the eight unique tiles is a combination of creative and functional factors. Firstly, the overall design is based on a photograph of Cradle Mountain, abstracted through Grasshopper into a pattern of multi-sized dimples, from 10mm depth to 35mm depth. Secondly, the convex surface of the larger dimples, when pressed against the structure creates a cavity between breather membrane and the surface of the sheet, eliminating the need for battens.

A jig was fabricated to facilitate forming of a standard sheet (2400mm by 1200mm) of aluminium, overcoming restrictions created by the size of the test jig. This reduces waste and the time and complexity involved in machining tile to tile connections. The potential for sheet deformation over such a large area was addressed by a 150mm bed of compacted sand beneath the sheet. The edges of the tiles are formed with a single linear trench, forming the overlap connection with adjacent tiles, above and below.

Each of the tiles took around an hour to be formed, with about 15 minutes required between tiles for set-up, including soothing the sand. The bed of sand was extremely effective in reducing sheet deformation, with the result that dimples across the tile were uniform in terms of depth.

Having developed fundamental design and fabrication parameters, the next step will be to identify circumstances and design approaches where ISF panels can demonstrably improve on existing cladding alternatives.

5. CONCLUSION

The DigiShed demonstrates to students a radically different and contemporary approach to building based around three emergent technologies; a semi-monocoque construction system that optimizes material characteristics, an assembly process that promotes articulate communication between all project participants and the basis for a highly customizable cladding option. The comparison with the TradShed indicates that FabTab is structurally, economically and environmentally viable. The work undertaken on the DigiShed – for example the dewpoint analysis - has had direct implications for applying
the system to the design of a larger scale commercial project. The AR guided manual assembly has been demonstrated to be articulate, however the technology needs to be tested in a training environment with participants less familiar with the logic of the construction system and the technology itself. The ISF cladding panels merit further exploration, particularly in terms of customization, structural performance and how they might contribute to the performance of the building envelope. It is in these areas that cladding formed by ISF might offer advantages over existing cladding alternatives.

References


