Urban prototypes: plywood architecture

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Abstract: The widespread availability of automated fabrication tools is rising dramatically. The pairing of CAD/CAM software and automated tools presents a shift in how the designer can take part in the manufacture process. This paper investigates how computing technologies can be effectively utilized to democratise the production of building components through simple design to build workflow, standardised building materials and CNC fabrication. Two dimensional sheet products such as plywood can easily be manipulated to create a large number of three-dimensional forms. By examining and adopting existing novel plywood construction techniques similar to an 'Ikea' like kit-set building systems effective construction methods were developed and produced. Basic CNC technology enabled the researchers to design and fabricate conventionally complex structures and artefacts without too much formal fabrication training. The projects however required large amount of preparation, prototyping and innovative thinking to overcome budget and material challenges. The success of the projects heavily relied on digitally produced components and a digital workflow specifically tailored to produce components for unskilled assembly build process.

Keywords: Digital fabrication; plywood; CNC.

1. Introduction

Technology is undoubtedly changing the way we practice architecture. Although students may be lacking in technical ability required for regulatory authorities, their exposure to software at universities is allowing for a new discourse in how architecture can be fabricated. Computer aided design (CAD) and computer aided manufacture (CAM) in particular has become a popular medium for students to express themselves through making. Students have become accustomed to ‘design to fabrication’ workflow with the use of digital fabrication tools. The construction industry in general is regarded to be a slow to uptake new technology. Although CAD/CAM is relatively a young subject within architecture, it is common place in the automotive, aerospace and shipbuilding industries (Leach, 2002). This same design to fabrication process is now becoming prevalent by practicing architectural practitioners throughout New Zealand
This paper is split into three sections. The first portion will review how digital innovation is enabling designers to play a larger role in the design to fabrication process. In the second portion, examples of existing applications of novel plywood construction systems will be presented. To finish, a review into the University of Auckland’s (UoA) School of Architecture and Planning (SoAP) Timber Technology Class will take place, before ultimately leading to the final discussion of the EDFAB project findings to date and its explorations with off-the-shelf construction products.

1.1. Innovation

When designers are presented with the task of designing products for the masses, a perception of mass production and commercialisation comes to mind. Producers add value to their standardised product lines by providing mass customised or made to order options. This normally comes at a higher cost, but consumers are willing to pay for individuality. The process of mass customization requires the consumer to directly engage with the manufacturer and is only possible through powerful design software that is simple and easy to use. The trend to personalise artefacts will continue to rise with further advances in automated machines (Sheil, 2012). Industries such as clothing, automotive, electronics, jewellery and publishing are already starting to take notice. Customisation of clothing and shoes has become a popular option for many consumers. Sporting brands like Nike, Adidas and Reebok provide basic designs that can be altered to match size, colour, type of material and labelling through their online web-stores.

More season designers can download open source 3D modelling software like Blender to design virtual objects, which in turn can be uploaded to online additive fabrication services - commonly named 3D printing - like Shapeways for rapid prototyping or final production. Turning our attention to 3D printing in the architecture field, many academics, engineers and architects around the globe are investigating how different types of large 3D printers can produce entire pieces of architecture. While many may be investigating very different materials and fabrication tool, the objectives remain the same. Engineer Erico Dini has created D-Shape, a large format 3D printer that uses sand and chemical binding agent to create a stone like material. His technology aims to target CAD/CAM architects like Universe Architecture to create full scale houses. Dus-Architects, in contrast has partnered up with Ultima to create an oversize desktop sized 3D printer called the KamerMaker. It has the ability to build large hollow components at 3.5 meters in height with bioplastic, with some sections to be filled with eco-concrete. Even though many are looking to develop a viable 3D printing solutions for architecture, the fact still remains that more research is needed before a commercially viable system can be produced (Fairs, 2013). The advantages 3D printing cannot be understated and holds the promise to push architectural aesthetic full of integrate detail and complexity.

Automated innovation in the New Zealand market-place is assisting with the development of 'modern methods of construction' in everyday building practise. Steel framing company FRAMECAD has developed a design, manufacture and build system dubbed the 'factory in a can' (Burgess, 2014). It is essentially an automated steel forming machine encased into a forty foot shipping container that produces steel framing components for building on-site. This portable mobile factory can be dropped off at any location to produce steel framing elements for commercial or housing projects on-demand. The flexibility of the system allows it to be useful for emergency relief housing and for projects in remote regions. The success of this product is recognised globally, where units have been utilized in a wide range of countries from Afghanistan to Brazil (Burgess, 2014).

Fletchers Aluminum, a window and door supplier has also been proactive with product innovation, with the development of the Smartfit system. It is a first of its kind in New Zealand and it is designed in
accordance to the New Zealand Building Code and practices. The product comes complete, ready for installation with no loose parts. Everything from the window flashings to the sill support bar are all integrated within the window, allowing for reduction in human error and time during installation. It must be noted, that without the use of an automated CNC machine this product could not be possible for mainstream production. The automated process also allows for made to order options, which will be discussed in the EDFAB section of this paper.

1.2. Designers as a maker

The term designer as a maker is a condition whereby the designer and fabricator are one and the same (Sheil, 2012). File-to-factory or CAD/CAM technology is enabling designers to directly communicate with fabricating machines such as CNC routers to produce goods. It has presented a shift to how the profession can approach and engage with design to production and as a result hold the promise of producing novel outcomes (Sheil, 2012). It can allow capability of manufacturing and construction to be a cohesive process, allowing for a creative dialogue between design and fabrication. If this type of working is pursued, one cannot work just as a designer or a fabricator, but as both; therefore, conventional thinking must be relinquished. The designer now must have the capacity to learn new skills, be adaptive and flexible to create design strategies. Another role digital fabrication technologies can play, is in the potential to bring back production from developing countries like China. The differences lie in the scale of production. Small groups or individuals can set up advanced design workshops armed with CNC routers, robotic arms, 3D printers, laser cutters and the more conventional hand-held tools (Bianchini and Maffei, 2012). In this way, crafted artefacts whether it is building components or furniture can be produced locally.

The advent of personal computing and other electronic gadgets has provided the younger and upcoming generations with a view of the world radically differently from the previous generations. This substantial shift in thinking is allowing them to usher in a technological and social change to challenge the way architecture is practiced (Kolarevic and Klinger, 2008). As a response, there is a growing trend for architectural graduates to take part in the building process through digital fabrication (Harper and Jackson, 2015). Many tertiary institutions such as the University of Westminster and London Metropolitan University provide design-build studios. Impressive results have allowed them to take part in Nevada’s Burning Man Festival and the Solar Decathlon Competition (Mamou-Mani and Burgess, 2015). Design to build Studio 19 hosted by Unitec Institute of Technology and Strachen group Architects is another great example of allowing students to take part in the construction of social housing.

Victoria University’s Makers of Architecture is a great example of how students can engage with design-build projects. Their built project ‘Warrander Studio’ boast the title of first entirely digitally designed and fabricated cross laminated timber (CLT) house in the country. What is impressive is the way four postgraduate students were able to push the boundaries of residential construction in New Zealand. Digital technology was not only used to minimise the need for skilled labour onsite, but also to develop a CLT specific cladding system. The team utilized paramedic software and CNC machining to create a ‘bed-frame’ like structure which accommodated everything from building paper to sheet cladding as prefabricated panel. Dubbed the Cassette Cladding system, it allowed the building to be assembled onsite and made water-tight all within a week, as the panels could be lifted and slotted into pre-routed slots of pre-assembled CLT structure. These panels are also designed to be easily detached for future maintenance or alteration (MakersofArchitecture, 2014).
The rise of design-build architectural practices cannot just be attributed to digital technologies, but to a specific way of thinking. Many recent graduates and young architects are just as comfortable banging away with a hammer, as with designing on a drawing board or three-dimensional model. Fluff Bakery, a tiny coffee shop in New York was designed and built by Lewis.Tsurumaki.Lewis Architects. The visually sensual bespoke interior was created by understanding the physical and visual attributes of plywood and inventing a novel application of it to creating a visual and tactile interior (Kellogg, 2006).

2. Plywood architecture

Plywood as a building product has existed for some time. It is a standardized product that may be overlooked. It is a versatile material that can be repurposed to make a large variety architectural products. In the past two decades, the gradual uptake of digital technologies and the advances in plywood production has allowed for innovation to occur.

Early innovator Larry Sass from the Massachusetts Institute of Technology researched how digital technologies and plywood could be used to solve the housing problems through digital fabrication. In 2008, at the 'Home Delivery' exhibit at Museum of Modern Art (MoMA) he presented the Instant House (citation). The result of the project identifies how plywood is an extremely dynamic material with the ability to be an effective medium for production of easy to handle structural and ornamental two dimensional components. Larry Sass (Sass, 2007) notes that the only ingredients and tools that are required are plywood, a CNC router, a rubber mallet, a crowbar and a computer.

The English based Facit Homes made famous by architectural show 'Grand Designs' has been manufacturing plywood homes for some time. Like FRAMECAD, Facit has also adopted mobile factory production systems for the creation of plywood building components. The use of BIM and proprietary plugin software enables Facit to parametrically design a site responsive architecture to meet their clients' needs and tastes (Bell and Southcombe, 2012). The difference between the Instant House and Facit Homes systems is how their two dimensional CNC plywood components are fitted together to form a three-dimensional modular panels — or chassis as Facit describes it — that act like oversized Lego blocks. Once these panels are added together to form the structural core of the building, it is made watertight using conventional building methodology. Cellulose insulation is pumped into the hollow cavities within the panels and internal linings are fitted to form the interior space. The design of this construction system has been developed with non-skilled labourers in mind to allow for greater human participation (Koones, 2014).

2.1. Community oriented design and fabrication

Digital fabrication is increasingly becoming accessible not just through universities, but through makerspaces and commercially available desktop machines, such as Makerbot and Formlabs 3D printers. Online forums and open source software is allowing many to build their own desktop devices. Dr Dermott McMeel (McMeel and Walker, 2015) from the University of Auckland, questions how these digital tools can disrupt the protected positions of the design and construction professions. How can a designer operate in communities with increased access to information, diverse expertise and new technologies? To what extent can design and construction be democratized?

Although open source software and services may seem to be free, there is a hidden associated cost. To form a successful social enterprise, a large amount of built-up knowledge has to take place through online forums and other community networks. The price of research, tools and expertise in these
projects is hard to quantify, but could be said to work on the basis of a gift economy. Like Linux software, other similar creative commons have started to pop up, such as ‘Instructables.com’ and Flicker.com. By sharing resources, such as knowledge, digitally connected communities can develop new construction methodologies. The concept of sharing knowledge is not new: the Walter Segal Self-build system is testament to this, existing well before the online open source initiative (Parvin, 2013).

Within a New Zealand context large interest has been poured into plywood community oriented construction systems. Two major systems that have made headlines are Wikihouse and Click-Raft. In a global context the WikiHouse organisation looks at how end demographic populations and local communities can empower themselves to solve housing problems. It is based on an open source architectural construction set where anyone can download free software – like Sketch Up – to individualize a library of predesigned flat pack templates (Galilee, 2012). Much like the Larry Sass Instant house two dimension components ‘printed’ from plywood will make up the flat pack building components. Wooden mallets, made from plywood, are the primary tool used to force friction joints together. They are designed with unskilled labourer in mind. The WikiHouse NZ Chapter, is a well-funded community organisation that resides in Christchurch. In short time, it has made strides in educating the local public and has developed a New Zealand specific WikiHouse construction system that differs to from its United Kingdom counterpart. Recent funding grants worth $300,000 from the Canterbury Community Trust is testament to its success (Harvie, 2015). The downside to the Wikihouse system is its complexity. The design relies on a large array of component parts that requires skilled and informed individuals to make a large array decisions (Stralen and Cezarino, 2015). When looking at WikihouseNZ, professional 3D modelling software Rhinoceros 3D is being utilized to detail and design their proof of the concept of the ‘Backyarder’.

Click-Raft by Wellington architect Chriss Moller is a New Zealand specific home-grown systems developed in New Zealand. The ‘Click-Raft’ construction system prides itself of how it can be adaptable and “adjusts to its environment in the sense that a tree does”. It is only possible to do this through its CNC milled plywood click-leafs and click-beams to form a lattice structure. They are simply clicked together to form floor, wall and roof elements in different configurations (Bell and Southcombe, 2012). What is interesting with the Click-Raft System is how its origins are not from a digital design background, but is are based on physics, mathematics and material science. It is only recently been conformed and made more user specific by CNC technology.

3. Student work

The Arts and Crafts movement rejected mass production and mechanisation. However, University of Auckland’s Mike Davis argues that the meaning of craft can have varying definitions, depending on context (Davis, 2013). Today, a craft in the context of production should also be identified with digital technologies. Understanding of material, learning how to create effective well-defined milling tool paths and finishing products are all traits of the practice of craft.

Even though technology can allow for a larger scope of participation, understanding and knowledge are key for successful results. If we look at MIT media lab’s Mediated Matter Group’s and their G3DP glass 3D printer, it is hard not to notice the array of disciplines that were needed for its conception and development. Collaborations and expertise had to come from not only MIT’s mechanical engineering department, but also from its Glass Lab and the Wyss Institute (Rosenfield, 2015). McMeel draws parallels to Karl Marx and his theories in regards to the dangers of dehumanizing production through the replacement of workers with technology. Our recent history of prefabrication has ultimately created
mass produced housing which seeks out to dehumanize production and force regularity to the landscape. As a new wave of technology is introduced, a responsibility lies with the designers not only to explore seductive forms and efficient construction, but how individuals and communities can be involved in the design and construction process (McMeel and Walker, 2015).

Experiences into design and construction of structure, ornamentation and weather proofing are highlighted with two simple construction case studies completed by students, researchers and lecturers at SoAP. The first study evaluates the successful MArch(prof) construction projects, in which a series of deceptively simple, but complex plywood 10m² structures were built. The second case study looks into the EDFAB’s prototype, a sleep-out built to investigate novel plywood house production.

3.1. Timber Technology Class

Drawing influence from WikiHouse and Click Raft, student Melanie Pau and Senior lecturer John Chapman re-invented the second semester Timber Technology Class in 2012. The first project entailed designing a plywood structure to improve safety and visibility at a primary school in a deprived area. In the following two years, four other shelters utilizing similar design and build principles were built. With each year, students built on and developed on the previous year’s construction techniques and in the process made new discoveries. The success of these projects has led to an established course within the SoAP which has subsequently received a number of international and national awards including Bentley Systems’ Scott Lofgren Student Design Awards and Design Institute of New Zealand’s Spatial Gold Pins.

Figure 1: The reciprocal structural system used in the 2013 Timber Technology Shelters.

Like WikiHouse, the selection of Plywood was seen to be a versatile product that not only could perform structurally and aesthetically. However, the standard size plywood sheet, 2400 x 1200mm was a limitation that had to be overcome. Over the years, different techniques where developed. A play with laminated portal frames was the original solution. The following year, a fear that the harsh New Zealand weather would delaminate the plywood resulted in a reciprocal structural system (figure 1.) similar to Alvaro Siza and Eduardo Souto de Moura 2005 Serpentine Gallery Pavilion to be utilized.
Limited budgets and technical skills required the students to be inventive. A turn to digital technology and the developments of a design to fabrication workflow allowed for basic design parameters and CAD/CAM process to be established. With every new built project, accumulated knowledge allowed for learning from past failures to be avoided. This meant that new students heavily relied on advice from former students, as well as workshop technicians, material suppliers, engineers and design tutors, who had already been involved with the digital design and fabrication class. In this context it was found that prototyping everything from 1:5 models to 1:1 physical mock-ups was an important step within the design process. It served as a means for the students to become familiar and comfortable with the digital technology on the one hand, and to avoid the risk of underestimating the complexities associated with the process of manual assembly.

The concept that one can simply just 'print' component parts or whole designs from a 3D model can be very misleading. It was found, every individual tantalised Radita plywood sheet manufactured in New Zealand varied in dimension and quality and therefore could not be quantified accurately within the digital world. It has been noted by Professor Michael Stacey that architects and engineers enjoy physical testing, as it can provide a source of confidence before final construction takes place (Stacey, 2005). This logic same logic has been applied to the timber technology class and it gives the confidence that they can build.

3.2. The EDFAB research project

The EDFAB: eco – digital fabrication is a research project, with the aim to challenge conventional processes and relationships and propose a radically new but viable design and building alternative. New attitudes towards application of material and the utilisation of digital fabrication methods are employed to produce distinctive, high quality, healthier and cost effective residential buildings that conform to the international passive housing standard.

Today, houses in general can be described as a collection of extensively tested and regulatory approved independent subassemblies. This form of construction is commonly viewed positively, due to the inability for housing to be prototyped and prefabricated. Manufacturers, however, can only realistically test their products with a few common auxiliary details. This can lead to large amount of frustration and liability for builders and designers within the realm of bespoke architecture. In most circumstances, designers are left to refine and coordinate all the sum of building subassemblies through the design, documentation and consent processes. Large projects in contrast, have the luxury to invest in the testing of full scaled mockups as cost normally can be recovered though large project runs (Mark Anderson and Anderson, 2007). This project aims to investigate how digital design and fabrication challenge the way we perceive “off-the-shelf” construction. Is there a way to produce a construction system that can mimic consumer friendly furniture concepts, where the complexity is engineered into the parts, leaving assembly process much simpler?

Early on in the development stage, a decision was made to take a large number of small steps, rather than over running the risk of getting bogged down in detail in one large step. This approach has been deemed successful and in less than a year, the EDFAB group have developed a proof of concept that is close to completion. The need for this prototype to adhere to regulatory code compliance confined the project to 10m2. Avoid applying for time consuming resource and building consents. At a later date, it is expected to build at a larger 70 to 100m2 dwelling for further examination. The aim of the project was initially to test the potential of a do it yourself approach, and to see if it can conform to the NZ
standards. It was found that extensive specialist and cross disciplinary knowledge was required in its realization.

The design of the EDFAB construction system required the designers to work closely with all consultants including the engineers and the passive house experts. This allowed for building code to be encoded into the design parameters. Drawing on expert knowledge early on in the design process was key to the success of the project. It must be noted, that increasing specialization and experts that was needed for this research project and can be argued that this workflow can be considered to be an expensive one. The pairing of digital technologies and off the shelf material allow for affordable prototyping to occur. In most cases, the time spent designing was greater than the physical testing. As a number of prototypes were conceived, new data was fed into digital models to allow the construction system to evolve. A simple digital work flow allowed development to be easy and all parties involved to be kept well informed about progress.

![Image]

Figure 2: The process of assembling the modules, fitting them into position and locking them into place with the ‘butterfly’ joint.

The final construction that was developed is similar to Facit Homes, where a 'kit of parts' were simply milled from plywood sheets to form modular panels similar to Facit Homes Chasis Panels. The prototype is divided into three sections, the primary structural modular panels, the secondary external envelope and the tertiary internal lining and fittings. To join and interlock the collection of panels, ‘butterfly plugs’ are hammered into place to form a well-braced structure (figure 2). The external envelope is designed to conform to the building code with off the shelf products. It requires the structure to be wrapped in building paper, followed by battens to form a cavity before being enclosed by timber cladding. Before the commencement of fitting the internal lining, insulation must be blown into the hollow sections within the modular panels. To create a thermally broken interior, insulation-tape will be used to cover all exposed interior joints in lieu of wrapping the internal walls with a vapor barrier membrane. To finish the interior fit out an insulated cavity made up of battens, plasterboard and plywood flooring. Issues like high wind and seismic load were required to take precedence over design details to allow it to meet local building regulations. As a result some elements of buildability and further systems for complex forms had to be sacrificed.
The CAD/CAM process allowed all the components to be CNC milled through simple, but effective production process. These components were assembled to form of the main structure at the Whau Arts festival by local unskilled volunteers. Following Larry Sass principle simple tools such as hammer, mallet and drill were only required and it ultimately lead to a large array of people to participating. The selection of light and durable plywood enabled for easy handling and allowed for mishaps to be easily forgiven. The design principle of symmetry, meant no component or panel could be assembled backwards or in the wrong order. This went along way for the volunteer’s confidence and enabled the sleep out structure to be built at speed.

The ProClima building wrap and for the most part, only required staples and flashing tapes for installation. Drawing attention to the construction of the Warrander Studio project, a trained builder was on hand to ensure to direct and ensure quality of build (MakersofArchitecture, 2014). The importance to use trained professionals during the construction process cannot be understated. The installation of the Diamond steel roofing was surprisingly easy to install, as train roofer was onsite to direct us and preform the more tricky tasks. As the EDFAB structure was built to very close tolerances an exact measurement could be provided to the window and door joiners from the computer model. As the door would be produced via automation, the team was confident that the door would fit. The Smartfit door in fact was the easiest building component to be installed, and only took about 10 minutes to put in place. Obvious problems however did come from the weight of the 2400 x 2500 mm door.

4. Conclusions

The timber technology classes have been successful for the development of UoA students. It serves a purpose and it does it well. The basic knowledge and techniques that were developed were instrumental in developing a digital fabrication culture with plywood at the SoAP. It could be said without it, the researchers of the EDFAB construction system would have spent extra time building that knowledge. It must be noted, the success of the EDFAB project also relied heavily on the cross disciplinary support within and outside the university. It came in the form of advice and recommendations on how to specify and apply off the shelf products. This can be seen in the selection of the Proclima building wrap, the application of the steel roofing and the installation of the Smartfit window.

The adoption of a radically rethought workflow, which involved multiple layers of prototyping, provided a medium for discourse between designer, material suppliers and other consultants. It ultimately led to the building of the 10m2 sleep-out for the purposes of testing the relationship between digital fabrication and social building. The use of simple tools in conjunction with ‘off the shelf’ doors, roofing and flashings to form a bespoke envelope turned out to be a cost effective solution for the project. To date, the sleep-out requires Knauf insulation to be blown into the modular panels by Eco Insulation, along with the fitting of the interior linings and electrical equipment. An oversight in the construction means the insulation should have been blown into the cavities prior to the installation of the interior butterfly joints. As a consequence, it now requires 60mm holes to be punctured into each individual panel to compensate. Missed opportunities in terms of shape and form of the panel modules could have been further explored. It may have reduced the amount of work and material to form the roof structure. Future developments entail making the system code compliant for buildings larger than 10m².
Acknowledgements

Special thanks Dr. Andrew Barrie, Dr. Paola Leardini, Dr. Manfredo Manfredini, Jon Davies, Elveso Togiamua, Dimitar Penchev, Franca Bertani and all the industry sponsors mentioned in this paper that made the built studies possible.

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