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Changing the Field: Recent Developments for the Future of Engineering and Construction

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Digital DIY : EDFAB project

Yusef Patel  
*(PhD Candidate, University Of Auckland, Auckland, New Zealand)*  
ypat013@aucklanduni.ac.nz

Dermott McMeel  
*(School Of Architecture & Planning, University Of Auckland, Auckland, New Zealand)*  
d.mcmeel@auckland.ac.nz

John Chapman  
*(School Of Architecture & Planning, University Of Auckland, Auckland, New Zealand)*  
jb.chapman@auckland.ac.nz

Abstract

The widespread availability of automated fabrication tools is rising dramatically. Entry-level CNC routers, robotics and 3D printers can be a cost effective machinery for small to medium sized enterprises to implement. The demand to reduce housing costs and to increase resilience and quality within the construction industry will lead to a dramatic change in how we build in the years to come. Today, one extreme of housing design remains defined by prefabrication, mass-produced ‘off the shelf’ materials and processes. At the other extreme, bespoke housing still requires designers to hire specialist consultants and tradespeople to calculate, engineer and manufacture custom made building elements, resulting in outcomes that are not always cost effective.

In this paper we outline EDFAB: eco – digital fabrication research project, with the aim to challenge conventional processes and relationships and propose a radically new but viable design and building alternative. To achieve these aims, the project is developing a system that introduces process and product innovation. It combines enhanced construction technologies, new attitudes towards materials and digital fabrication methods to produce distinctive, high quality, healthier and cost effective residential buildings that conform to the international housing standard. The paper discusses the specific contribution to the project from the different involved research areas – building technology, architecture and digital fabrication technologies - and presents the early results towards a ‘do it yourself’ (DIY) 10m² prototype domestic scale ‘sleep out’, designed and built using CNC routers and novel plywood construction methods that produce a kit-of-parts that are very easy to handle.

Keywords  
Digital Fabrication, Prefabrication, Housing, Mass Customization

1. Introduction

The building industry is currently experiencing change through the means of a technological revolution, whereby search for innovation is ever pushed the boundaries. The publicity that is being placed into additive layering manufacturing (commonly known as 3D printing) shows that there is a general acceptance towards digital fabrication. While a large amount of research is being placed into pushing
structural and aesthetic boundaries of digitally produced architecture, there is little is in the way of viable affordable digital DIY architecture. Opportunities exist for non-specialists to take part in digital architecture through the means of user-friendly software and simple to use basic automated fabricating tools.

This paper will firstly discuss a brief history of prefabrication, which reveals how some of the current strategies regarding automated construction have their origins in the seventeenth and nineteenth century. A study of international and domestic construction approaches will take place, before a outlining of the EDFAB, eco - digital fabrication project and the specific concepts and motivations that drove it. Finally ending with a review of the project and possible future research.

2. A History

Digital technologies are providing a vital evolutionary step to the prefabrication process. The manufacturing of building components offsite to be subsequently assembled onsite has historically taken place as early as the seventeenth century with colonization of remote colonies by European Settlers. The introduction of standardization – a product of the industrial revolution – is an early example of how mass-produced material has the ability to be made into a ‘kit of parts’ for the creation of efficient building systems. The Crystal Palace designed by Joseph Paxton for the 1851 Great exhibition is a prime example of how standardization of iron component parts has contributed to uptake of prefabrication during the industrial era. This methodology of construction allowed architecture and infrastructure – such as bridges and trains stations – to be built at considerably less cost and time, but with an enhanced quality over the masonry and timber alternatives (Smith, 2010).

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 (Anderson & Anderson, 2007).

Homeowners often have a fixation to personalize their homes through DIY exercises. This demonstrates how standardization has rendered the built landscape to become visually uniform. However without it, buildings would not be constructed to a standard of efficiency and quality that is currently expected today. Even though there are a limited number of automakers worldwide, they achieve a large variety of products for consumers to select from. Modularization and technology has enabled customer satisfaction to be addressed by through the means of providing an option to individualize during the production process. The housing industry by contrast has a large pool of designers who are reliant on a limited set of standardized subassemblies. It draws to the conclusion that perhaps it could be said that builders are superficially manufacturing bespoke housing. The auto industry may not be an appropriate model for the highest aspirations of architecture, but it can be an influence to how we build homes through the economies of modularized production (Anderson & Anderson, 2007).

3. Automated construction

In the following section will look at examples of three strategies for design and construction. The first strategy looks into factory output with the examination of ‘Toyota Homes’ and ‘Concision’ panelized technology. While the second strategy investigates CNC plywood construction with Larry Sass’s ‘Instant House’ and Alastair Parvin’s ‘WikiHouse’. Lastly the final strategy looks at ‘FRAMECAD’ and ‘Facit Homes’ mobile factory systems.
Each year, a set of new automobile models are produced, many of which are modifications of the previous year’s product. The manufacture and design of automobiles is centered on a primary internal framework – commonly referred as the chassis – and the secondary interchangeable internal and external components like the engine and the body shell. Over several years, refinements to the primary and secondary components take place for greater cost effectiveness and user performance. The supply of basic models along with the options of customization adds value to a product, as it has the capability of providing for a larger section of customers, rather than a select few (Anderson & Anderson, 2007). Toyota Corporation constructs and sells its residential homes similarly to their automotive wing. It provides a two tier service, with the first option for allowing customers to choose from ready-made modules, with add-on alterations to suit user preferences. In the second option, customers can request an architect to design a bespoke home that meets their specific exactions at a higher cost. Each home is made up of approximately twelve large steel-frame structural core modules that figuratively act like automobile chassis. The configuration and the relationship between the modules, provide a simple inexpensive way to customize space, although it must adhere to a set of structural and manufacturing parameters to ensure product integrity. A catalogue of different types of claddings, colours, exterior and interior fittings are selected by the homeowner to further contribute to a personal architectural product. These secondary add-on elements have the ability to be customized, as they are produced on-demand from set of raw materials (Adulfahem, 2012). The importance of working with modular economies should not be understated. Toyota’s production techniques are heavily reliant on automated manufacturing techniques and expensive infrastructure that may not be feasible for many smaller economies such as New Zealand.

Christchurch Concision and smaller Auckland based eHomes are examples of large-scale automated modular panel construction that service domestic and commercial building markets. Concision alone can produce approximately 1000 homes at their Christchurch factory. The factories do not come cheap. They require large capital investments of around 19 million dollars (Wood, 2014). Concision modular panels differs to panelized systems like engineered sandwich SIP and CLT panels as they are literally sections of walls, floors and roofing that are fully fitted with insulation, plumbing and electrical and other relevant subassemblies. The use of sophisticated software is used to translate bespoke building design into production outputs for the digital manufacture of the modular panels. The transportation and assembly of these panels by crane to form a watertight building is a quick process (Wood, 2014). What is interesting with Concision building technology is how it is modeled around conventional building system and could be possibly a ruse to satisfy local building codes and standards. The recent earthquakes in Canterbury, New Zealand have provided added motivation for larger uptake of automated construction technology. At the one side, there will be an added benefit to replace the large stocks of damaged building with speed and high standard in the short term and at the other it will be possible to meet a growing housing demand in other urban centers, this is a good opportunity for replacing substandard building construction built over the decades.

Plywood as a material is no stranger to digital sponsored design. The research projects ‘Instant House’ by Massachusetts Institute of Technology and the highly published WikiHouse experiments are just two examples among many others that are innovating with CNC router fabrication technology with composite panelized products. The ‘Instant House’ is a proof of concept that investigates the capabilities of CAD/CAM – computer aided design and computer aided manufacture – with plywood, for the purpose of creating a customizable housing systems for emerging communities (Paio et al, 2012). The result of the project identifies that plywood is an extremely dynamic material with the ability to be an effective medium for production of easy to handle structural and ornamental components (Sass, 2007). WikiHouse on the other hand 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 – Sketch Up and WikiHouse plugin – to individualize a library of predesigned flat pack templates, that can be likened to IKEA furniture products (Galilee, 2012). The use
of basic tools, such wooden mallets to force friction joints together shows that the detailing within the WikiHouse system compatible to unskilled labour.

In most cases, the manufacture of prefabricated components and modules takes place offsite in controlled environments. Automated machines provide an alternative to this concept, as it is now possible to set up a controlled fabrication environment onsite. FRAMeCAD mobile factory system is a commercially available system that produces components for building onsite. It is a portable ‘self-contained facility’ that can be dropped off at any location and has the capability 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. This type of construction has also been adopted by the design-build firm Facit Homes with the development of their CNC milling mobile factory for the manufacture of hi-specification bespoke homes with plywood.

The use of BIM and proprietary plugin software enables the Facit Homes to parametrically design a site responsive architecture that meet their clients’ needs and taste. The same software enables every detail to be converted into commands for CNC manufacturing, creating a symbiotic relationship between design and production (Bell & Simpkin, 2013). Facit Homes draws parallels to Toyota Homes principles of modular efficiencies. It can be seen in how adaptive CNC plywood components are fitted together to form a three dimensional modular panels – or chassis as Facit literally describes it – that act like oversized Lego blocks. Once a collection of these modular panels are added together to form the structural core of the building, it is made watertight. Cellulose insulation is pumped into the hollow cavities within the panels and internal linings are fitted. What is significant in this system is that it humanizes the digital fabrication, by allowing non-skilled workers to participate and ‘get their hands dirty’ as seen in the construction of the Herftfordshire House (Koones, 2014).

Even though all of the construction systems discussed in this section all slightly focus on different manufacturing outputs, it is evident that there are two conditions which can contribute to a successful housing construction system. The first is the primary material – like coil steel or sheet plywood – that can be used to create a structural modular construction system. The second is the ability to adapt to specified conditions and briefs, thus allowing individualization of architectural space to occur.

4. Concept and Methodology

DIY culture can be attributed to society’s strive for individuality. However acquiring fabrication knowledge, skills and tools to fulfill it can take time. Digital fabrication can effectively remove this obstacle and encourage a larger population to participate. Simple fabrication CAD files made using dedicated open source software and online web applications allows greater general public access to digital manufacturing technologies. Jewelry design with open source software like ‘Blender,’ provides the opportunity for a user to create virtual models, which in turn can be used to 3D print objects. Third party on-demand online print services like Shapeways or sketchup provides affordable services and has the ability to reach anyone, anytime and anyplace. As 3d printing becomes more commonly available, its novelty will fade. The meaning behind bespoke production will thus be redefined.

The EDFAB project aims to investigate how best to utilize simple digital design tools to produce a New Zealand specific DIY housing set. The theme of modular plywood construction was deemed to be an appropriate system due to its inherent properties to allow for conversation between parametric modelling and production demands. The appropriate housing examples – Instant House, WikiHouse and Facit Homes - are not indigenous to the New Zealand context and need to be tested to local conditions. Some issues like high wind and seismic loads were required to take precedence over design details to allow it to meet local building regulations. As a result some elements of buildability had to be sacrificed. The EDFAB system is divided into three sections, the primary structural modular panels, the secondary external envelope and the tertiary internal lining and fittings. The EDFAB modular panels could be said
to be a cross between sandwich panels, Facit Lego modules and conventional timber framing methodologies. To join and interlock the collection of panels, ‘butterfly plugs’ are hammered into place to form a well-braced structure as shown in figure 1. The external envelope is designed to conform to the building code. It requires the structure to be wrapped in building paper, followed by battens to form a cavity before being enclosed by CNC milled Shadowclad plywood 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 is 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 are erected.

![Image 1](image1.jpg)

**Figure 1:** The process of assembling the modules, fitting them into position and locking them into place with the ‘butterfly’ joint.

Online publishing enterprise ‘Blurb’ has used technology to disrupt the supply of printed books. The idea of creating one’s ‘own book’ can require large sums of capital, whether it is for publishing anything from a thousand copies to just a few. Authors can empower themselves through Blurb’s computer applications and word processing plugins to design and upload products for a cost effective on-demand printing. EDFAB is similar in its approach, but with obvious limitations. The prototype software that was designed for the EdFAB construction system was split into the primary ‘end-user interface’ (eUI) and the secondary ‘expert user interface’ (xUI). The first half the process enables any user to parametrically design a space to suit their expectations using the eUI software package. The second half of that process allows design professionals to import the eUI data to the secondary xUI software to produce building consents and CAD/CAM outputs for manufacture. This theme of empowering individuals who are foreign
to digital DIY production was tested with the design and manufacture of a Christmas tree (figure 2) for a local pre-school. A volunteer was given the task to partake in this exercise by designing the artifact with mainstream software Adobe Illustrator (AI). After watching a few tutorials on YouTube a vector based AI file was produced and transferred to Rhinoceros 3D to allow a user-friendly plugin RhinoCAM to produce a set of instructions in G-Code to communicate with the CNC router for the easy production of the artifact. The form of participation was desirable for the volunteer, as he felt safe and comfortable to learn and produce inputs for digital manufacture without the risk of needing to completely understand the details for digital production.

5. Prototyping

It was deduced that a physical 10m² ‘sleep out’ proof of concept was needed to be constructed for evaluation purposes. Two major factors needed to be analyzed, with the first looking at how human interaction could converse with digital sponsored production and in the second with how a modular plywood structure would react in the New Zealand context. Prototyping became prerequisite to the design of the construction set, where large amounts of time were invested into creating scaled architectural models and 1:1 detail mock ups (figure 3). In total one 1:10 concept model, two 1:6 laser cut models, three 1:1 detail mock ups and countless joinery models where produced to evaluate and develop the shortcomings that lay in the EDFAB construction system. Prototyping in the design process, allowed human participation and material properties to be effectively simulated and lead to some keystone findings and without it fundamental discussions that shaped the construction system could not take place.

The prototyping phase became interactive points of discussion for specialist - engineers, technicians, designers and consultants – to actively take part early on in the design process, which is in stark contrast to orthodox design practice, where they are introduced at a later stage. As a result, the limitations within the system where found early in the design process and were corrected before large production runs. In fact the knowledge provided by specialist early in the development of the EDFAB construction system drove the project forward. During the testing of the 1:1 detail mock ups, it was found that it is not always desirable or possible to automate all aspects, therefore it become necessary to call upon expertise. Traditional skills such as manufacturing, structural and environmental design expertise were adopted early in the design phases and remained critical throughout all steps undertaken. If the group work between all the parties involved has not been established and layered well from the beginning, the overall construction system could have been compromised.

Figure 3: Scaled architectural 1:6 model, 1:1 cladding model and 1:1 structural prototype

Material limitation – specifically in respect to plywood – became a major study with the EDFAB project. Locally available New Zealand structural Pinus Radiata plywood – generally used for sheathing – is not
as dimensionally stable when compared to its European counterparts. Latvian Birch used by Facit Homes appeared to be the most suitable. However the associated perceptions of it being defined as a high-specification material that is commonly used in the furniture deemed it to be too pricy. Chilean plywood was also experimented with, but it was also found to be a challenging product for the CNC mill. The cost effective Meranti marine plywood from Malaysia was found to be desirable in terms of quality, but due to it being too heavy it became unfeasible to work with. At a later stage, a lighter version of the Meranti plywood called ‘Marinelite’ was found and became the primary material for the 10m² sleep out. Even with the issues found with the different selected plywood variants, it was still possible to construct 1:1 sectional detail prototypes.

6. Analysis

Drawing influence from Wikihoue and Facit Homes, simple CNC assembly techniques were developed. Simple tools where required – hammer, mallet and drill – meant a large array of people could participate (best seen in Figure 1 where components where easily assembled into modules using basic hand tools). The selection of light and durable plywood enabled for easy handling and allowed for mishaps to be easily forgiven. All these traits allowed volunteers to contribute in every process of the physical build.

The design of the components that made up modular panels where customizable. This proved to be useful, as it allowed the panels to conform to different floor areas. However, the design of the wall module became problematic as it was confined to the parameters of plywood (2400 mm x 1200 mm). When the internal lining was added to the interior, the floor to ceiling height dimension was reduced to 2200 mm. A scheme to counteract this predicament to increase wall panel height to 3600 mm was implemented but was ultimately highly problematic as it increased the complexity of the components to make the wall module, substantially reducing ease of assembly.

The unexpected problem of ‘creep’ was found in the 1:6 scaled models and 1:1 prototypes. This phenomenon is caused when small deviations in the physical construction are accumulated over the length of the building, resulting in the combined components to be of a different length than intended. This problem is highlighted by Larry Sass (Sass, 2007) in respect to the design of the Instant House. He draws attention to how traditional building systems are designed for paper based communication, hand craft and inaccurate assembly methods and do not have capabilities to be transferred to the precise nature of digital design and manufacture. The needs to be a digital integrated method to link the design, production and assembly process to produce disable results. The large amount of orthodox construction techniques that are imbedded into digital practise, the probability of unwanted imprecise outputs will govern the practise of building (Sass, 2007). This draws us to the fact, all construction elements - material, manufacturing systems, assembly process – needs to be synchronized via automation. These systems do exist, with Kajima ‘AMURAD’ onsite construction factory being one of many examples. The downside to these systems is highly expensive and complex infrastructure that only large densely populated bases, with certain type economic condition are able to support (Jecob, 2012). Like the Sass experiments with the Instant House, prototyping enable a homogenized system to be developed, and thus reducing the impact of human touch. Acceptance to this imperfection however, is needed when working naturally grown materials such as plywood or with DIY enthusiast as it can never be eliminated. In reality, nothing is as perfect as portrayed in the digital world and therefore traditional knowledge and craft cannot be eliminated when fabricating architecture.
Figure 4: The completed structure core and a proposed artistic render of what the finished 10m² sleep out may look like

7. Conclusions and Future work

The principles of modular design became a large element when formulating the EdFab construction system. The combination of easy to access ‘off the shelf’ material, easy to use accessible software and CNC milling technology enabled participation from the interested and the enthusiast. The inability for software to completely predict the realities of construction meant physical prototyping was required. Results revealed that skill and expertise was critical to successfully develop, manufacture and implement a human centric digital construction system. With the future completion of the sleep out, the conditions presented in this paper will be further scrutinized. To date, the structural core is complete while the exterior envelope and interior linings still to be experimented with (figure 4).

5. References


