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File to Factory: A case study
of automated prefabrication
house-building methods for
small-to-medium enterprises

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By Yusef Patel



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File to Factory: A case study of automated prefabrication house-building methods for small-to-medium enterprises

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ABSTRACT

The Eco-Digital Fabrication (EDFAB) research project aimed to investigate how automated prefabrication technologies and off-the-shelf construction products can be employed to disrupt building industry norms. The aim of this research – conducted at the University of Auckland and Unitec Institute of Technology from 2014 onward – was to provide small-to-medium enterprises in the construction industry with a pathway to upskill and increase construction productivity through the use of these processes. The availability of automated machines and easy-to-use fabrication software is increasing dramatically and this can be paired with readily-available construction products to produce novel mass-customised housing solutions.

The application of basic automated technologies – such as CNC (Computer Numerical Control) routers – allowed researchers to create ‘recipes’ that can be adopted and adapted relatively easily. By no means did the research favour digital manufacture or assembly processes over

traditional analogue construction techniques – the goal was to provide logical, productive and accessible blended solutions for greater affordability and flexibility in design. For example, the designed experiments were required to be built from readily available products, and used simple readymade screw fixings rather than digitally-produced custom fixings or joining mechanisms. The research project aimed to generate discussion and provide recommendations on how the construction industry might support the adoption of automated prefabrication technology in small-to-medium enterprise (SME).

INTRODUCTION

Engaging with technological innovation is no longer considered an overly expensive exercise. Current trends point to a future whereby local backyard or suburban enterprise can thrive alongside larger factory 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 & Maffei, 2012). Within secondary education, there is already a significant push towards computational learning and making in evidence. For example, Henderson High School in West Auckland already teaches basic digital fabrication technologies with their own laser cutters and 3D printers.

Various community-oriented makerspaces and commercially-run digital fabrication services now

cater to individuals with varying backgrounds and levels of experience. Online resources and communities can allow anyone to develop the necessary digital skills and expertise to converse with automated machines without any associated cost. This concept of sharing knowledge is not new: Walter Segal's self-build system is testament to this, existing well before online open-source initiatives became commonplace (Parvin, 2013).

In response to technological change, a cross-disciplinary team consisting of architects, technicians, engineers and industry product suppliers came together to understand how best to formulate solutions for the construction industry in New Zealand. Ultimately, the goal of the research was to investigate how labour, design process, organisation, productivity and quality can be supplemented by technology through the production of a series of experimental prototypes under the banner of the Eco-Digital Fabrication (EDFAB) project. To ensure everyday building contractors and product suppliers in the construction industry were not alienated, viable and readily available off-the-shelf materials and systems needed to be incorporated into the experimental prototype proposals.

COUNTING THE COST

The price of building a house in New Zealand is approximately fifteen to twenty percent greater than in neighbouring Australia. The distributed cost in New Zealand can be divided between land – which includes developing, design and planning fees – and the cost of materials and labour. Forty percent of the capital sum required for a new home is attributed to the purchasing of land, followed by materials and labour at thirty percent and twenty percent respectively (Page, 2009).

The high cost of materials in New Zealand can be attributed to our economy's inability to produce and manufacture products at required scales, and the domination of the market by large monopolies (Macfie, 2012). Inefficiencies in the labour market have equally affected productivity and access to skilled tradespeople. Part of the problem lies with ninety percent of

builders or building companies having fewer than five employees and, of those, about sixty percent being sole practitioners who build one house per year (Bierre, Howden-Chapman, & Early, 2013). Another problem is presented by gender inequality – only thirteen percent of today's construction industry are women (Hutching, 2017). The inclusion of more women into the construction labour force could effectively alleviate the present skill shortage.

The recent demands for higher-performance building outcomes – specifically to create warmer and drier homes – in a market that is in dire need of greater levels of skilled labour, further increases the capital needed to construct homes (Page, 2009).

CUSTOMISATION IN HOUSING

The reality is that Kiwis are paying bespoke housing prices, even when house construction in New Zealand uses mainly extensively tested off-the-shelf products. Every aspect of the product is required to conform to a set of specified auxiliary details that are required to be followed for both regulatory and guarantee approvals. Consequently, large portions of new houses are being constructed with a limited set of products, and the only real design individuality is in composition (Anderson & Anderson, 2007).

If this is the case, is it surely not acceptable to continue to impose such a level of standardisation on house building. A solution could be provided by generating a catalogue of limited and quantifiable options containing features such as colour range, fittings, window sizes and space layout, contributing to significant cost savings in both planning and building phases (Page & Norman, 2014).

Automated construction can provide options that are site- and customer-responsive through mass customisation technologies (Bell & Southcombe, 2012). The process of mass customisation requires the consumer to directly engage with the manufacturer, and is only possible through powerful design software that is, fortunately, simple and easy to use. The trend to increasingly personalise artefacts will continue with further

advances in automated machines (Sheil, 2012). Producers add value to their standardised product lines by providing mass-customised or made-to-order options. This option normally comes at a higher cost and really only allows the consumer to personalise rather than create something truly unique or bespoke.

Historically, prefabrication has created a fine line between repetitive banality and superficial chaos. The former was well represented by the Levittown housing development built on Long Island, New York, at the end of the 1940s, while the catalogue homes that dominated the Scandinavian housing landscape in the 1960s represented the latter. The Levittown houses were spatially rigid in format, meaning there was very little room for innovation and variation, which led to the development being described as “little boxes made of tick-tacky” (Reynolds, 1962, cited in Bell & Southcombe, 2012, p. 47). The wide range of catalogue house-building companies in Scandinavia, on the other hand, eventually required the application of planning regulations in order to control the abundance of unruly variation (Waern, 2008). Today, the added dimension of mass customisation through automation can produce homogeneity in design outcomes, and in the process diminish architectural creativity. Software, therefore, has the potential to, at the extreme, either create copies of buildings designed to conform to conditions, or produce overly complex architecture.

AUTOMATED CONSTRUCTION

Technology is undoubtedly changing the way we practice the production of architecture, specifically with ‘file-to-factory’ or computer-aided design and computer-aided manufacture (CAD/CAM) enabling designers to directly communicate with fabricating machines such as CNC routers to produce goods. Although CAD/CAM is well integrated into automotive, aerospace and shipbuilding industries, it is still relatively new in architecture (Leach, 2002), and it presents a shift in how the profession can approach and engage with production of novel outcomes (Sheil, 2012). Contrary to popular belief, New Zealand is actively taking part in this form of automated construction.

The Auckland-based steel framing company FRAMECAD has developed a design, with a manufacture and build system, dubbed the “factory in a can” (Burgess, 2014, para. 2). It is essentially an automated steel-forming machine, encased in a standard forty-foot shipping container, that produces steel framing components for building onsite. This 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, units having been utilised in a wide range of countries from Afghanistan to Brazil (Burgess, 2014).

The current automated prefabrication market can be divided into three digital categories. The first option delivers to the mass-market housing industry – it comprises pre-nail and automated factory production processes. The second manufactures bespoke or high-end architecture for the wealthy. The third, still relatively untapped, option involves open-source, online DIY systems that allow for end-users to download, customise and print files on CNC machines for subsequent assembly by lay-people.

Mass-market housing is dominated by a large-production output processes that generally reorganise the way products may be manufactured. In most cases, elements are built to the same standard as conventional construction systems or singular modular elements such as cross-laminated timber (CLT) panel or Metrapanels. Concision’s modular panelised technology, for example, uses elaborate production processes to force automated tools into mimicking conventional construction by creating modular panels for subsequent assembly onsite. These panels differ from panelised systems such as 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 (Wood, 2014).

On one hand, the concision process can be viewed as providing builders, technicians and

other specialists with the means to upskill, while on the other it can create exclusivity in the labour market and reduce the availability of work for the everyday blue-collar worker. Because, for the most part, the same manufacturing methods employed in these processes can be used by an everyday skilled labourer, productivity gains are with made in the performance and the bespoke area. Some argue that these large enterprises require substantial setup costs, demand and popularity to be viable, or risk facing the consequences of receivership as Auckland's eHomes did in 2015 (Gibson, 2015). Given the current Auckland housing crisis, firms like Concision must be commended for venturing out and pushing the boundaries of construction to solve a systemic industry problem.

The UK-based Facit Homes is an example of a small group of skilled professionals that produces bespoke modular plywood homes using basic CNC technology. The use of Building Information Modelling (BIM) and plugin software affords the Facit design team the ability to meet the client's needs and tastes proprietarily, responsively and efficiently (Bell & Simpkin, 2013). Facit's system is based on assembling customised two-dimensional CNC plywood components together to form three-dimensional modular panels – or 'chassis' – that act like oversized Lego blocks. Once these panels are put together to form the structural core of the building it is made watertight using conventional building methods. The design of this construction system has been developed with non-skilled labourers in mind to allow for greater human participation (Koones, 2014).

Innovator Larry Sass from the Massachusetts Institute of Technology explored how digital technologies and plywood could be used to solve community housing problems through digital fabrication and social enterprise. In 2008 he presented *The Instant House* at the 'Home Delivery' exhibit at the Museum of Modern Art (MoMA) in New York. The results of the research identified that 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. Sass (2007) notes that the only ingredients and tools

that are required are plywood, a CNC router, rubber mallet, crowbar and computer. Today, the online open-source market has taken to this form of building enterprise, with the global organisation Wikihouse or the local operation Click-Raft gaining momentum.

The progress Wikihouse and Click-Raft have made in democratising production is remarkable, however, the systems are reliant on too many factors. A major fault within the design of the Wikihouse construction system, for example, is in the resistance to forgo certain inefficient construction details due to concerns it will become inaccessible to everyday people. This anxiety is unfounded, as human skill, knowledge and understanding are still required to implement design through digital fabrication or to even apply to regulatory agencies within the New Zealand context.

To contribute to research in this area, the architectural education programmes at the University of Auckland and Unitec Institute of Technology created design-build programmes centred around CNC production to provide communities at Onehunga Primary School and Te Puti Marae with much-needed shelters. The projects are examples of how Pasifika and Māori communities can be served by technology when site restrictions and limited budgets can impede the implementation of a project.

In the case of the design and construction of the whare kai at Te Pute Marae, a Wikihouse-type construction method was employed: flat-pack components were CNC fabricated at Unitec's architecture workshop, transported to the site by trailer and by jetboat across the Whanganui River, and carried up a river bank to the settlement, for assembly by the students like a large jigsaw puzzle. The process was simple and allowed for a difficult situation to be resolved in an affordable and efficient manner.

Today, Māori groups are as keen as ever to contribute to and provide solutions for the creation of community housing and developing technological innovations to improve outcomes. Various Treaty of Waitangi settlements have provided resources to iwi and hapu to contribute to and increase affordable housing stocks in

Auckland and nationally (Cook, 2017). The New Zealand Government's Housing Innovation Fund provides grants for "[t]hird sector providers – such as community trusts and iwi organisations that are focused on socially oriented business – to build or buy community rental facilities and supply affordable home options" (Schrader, 2007, para. 83).

Te Rūnanga o Kirikiriroa's investment in the creation of a steel framing factory is an example of how Māori are supporting the development of innovative construction tools that will in turn provide the community with employment opportunities (Akuhata, 2009) and efficiencies that timber framing cannot provide. Within the educational and training realms, positive steps are being made by the He Korowau Trust to arm young adults with trade skills to contribute to building and maintaining housing in the Northland region (Koti, 2017). Progressive housing developer Ockham Residential and Marutūahu iwi are building the affordable Tuatahi apartments in Mt Albert, Auckland. The partnership is socially responsible and provides lower-cost housing options to young couples, solo parents and the elderly who want to live in the popular city-fringe suburb (Miller, 2017).

SMALL-TO-MEDIUM ENTERPRISES AND AUTOMATION

Current opinion about automation seems to be split, one side favouring change, innovation and progress, and the other opposing change, likely out of fear or misunderstanding. When architecture is compared to construction, the former is more progressive within society, but when compared to the sciences it is less inquisitive and experimental. Within the construction industry – which includes suppliers and material producers – there is a tendency to orient decisions and targets towards large population numbers (Anderson & Anderson, 2007). In New Zealand SMEs dominate the landscape, so it is not surprising that the construction industry seeks to cater to their needs and requirements. An approach is required that will educate, upskill and innovate to diversify the construction industry use of readily available materials and knowledge processes without heavy capital investment.

Within construction, competition is generally based on cost advantage rather than a technological edge, while in architecture, personal commitment from individuals, small groups of creatives or technological enthusiasts remain the main source of innovation. A lot of experimental work is beyond an architect's normal commissioned work (Anderson & Anderson, 2007), but innovation can be seen in the way Wellington-based SME Makers of Architecture has approached construction. Unlike Facit Homes, Makers have tapped into both local backyard and large factory production to further their architectural reach. Their debut project, the Warrander Studio, boasts the title of the first entirely digitally designed and fabricated cross-laminated timber (CLT) house in the country. The founding team consisted of four architectural graduates bound together by the simple aim to push the boundaries of architectural fabrication.

Digital technology was not only used to minimise the need for skilled labour onsite, but also to develop a CLT-specific cladding system (Chapman, 2014). The team utilised parametric software and CNC machining to create a 'bed-frame'-like structure which accommodated everything from building paper to sheet cladding for the prefabricated panel. Dubbed the 'Cassette Cladding System', it allowed the building to be assembled onsite and made watertight within a week, as the panels could be lifted and placed into pre-routed slots in a pre-assembled CLT structure. These panels are also designed to be easily detached for future maintenance or alteration, and ultimately the project outcomes produced affordable houses with speed and efficiency (Marriage & Sutherland, 2014). It must be recognised that Makers of Architecture push for innovation within the highly bespoke marketplace niche. Their system is heavily based on complex computation systems and expensive workflows. Simply put, the majority of their work takes place on the computer, therefore questions remain as to how the majority of conventional builders could take part in this construction process beyond the ultimate assembly.

DESIGN METHOD

Complex forms can be easily produced in a

digital environment, however, to realise them in the physical world can be overwhelming should an incorrect approach inform production (Sass, 2007). The design process in an architectural practice is not so dissimilar to the iterative process used in science experiments to resolve a problem (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 later on (Anderson & Anderson, 2007).

If the design and construction team can test the design before committing it to the contractual process they can afford to be more ambitious – although they must be confident, since there is rarely enough time for major changes to be implemented (Thornton, 2005). There is still room for conventional construction methods here even though they cannot produce the same levels of accuracy as a digitally-produced artefact. However, when an appropriate workflow is applied, the making process of such a blended analogue and digital process is not as complicated as many are led to believe (Willis & Woodward, 2010).

MATERIALITY AND TOLERANCE

The emblematic work of Walter Gropius and Konrad Wachsmann at the Bauhaus in pre-war Germany was prototyped with panelised systems. Their research eventually led, in 1943, to huge funding support at government and corporate level to begin planning large-scale factory-based production (Anderson & 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 frequent prototyping – the results created 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 that manufactured suitable tolerances affected output, leading the enterprise to bankruptcy (Bergdoll, 2008).

With advances in digital fabrication, many believe

tolerances can be reduced to zero. Pinpoint precision may be attainable for particular production circumstances, but thought must be spared for material physics and environmental conditions (Malé-Aleman & Portell, 2014) when constructing architecture. Tolerance needs to be integrated into the design process to realise a successful project (Parsons, 2014). This requires three-dimensional virtual models to be vetted through prototyping to ensure it is constantly updated with relevant construction tolerances and to make sure imperfections are ironed out (Willis & Woodward, 2010).

TECHNOLOGY AND SOFTWARE

Modelling conceptual ideas in 3D digital space provides an environment where information can be readily available to designers and fabricators. A great benefit of architectural software is its ability to create successive design iterations efficiently. Embedded data can be utilised to generate scaled prototyping, visualisations and quantity-surveying information (Iwamoto, 2009). The obvious advantages of working within a digital environment over an analogue process is the way information can be manipulated, transferred and replicated with ease (Dunn & Felsen, 2012). For example, if an architect needed to change a hand-drawn design, it would entail a laborious process of redrawing. Again, if a physical conceptual model was required to be made by hand for spatial validation, the designer would have to physically measure, draw, hand-cut, check and assemble it, rather than simply extracting data from a virtual model and printing it via a laser cutter or 3D printer.

However, questions remain as to what extent design and construction can be democratised (McMeel & Walker, 2015). As the uptake of digital technologies increases, given the ease of use involved, levels of individual production skill and expertise will diminish (Parsons, 2014). How will the future generation of architects cope when the machine fails, or simply does not produce what is required, if they do not have well-rounded understanding and expertise to fall back on?

If the gap between physical and digital is continuing to increase, it will require the

architect or designer to increasingly collaborate to acquire the skill, imagination and expertise of the craftsperson. It is likely that prototyping equipment and CNC-produced mock-ups will become a regular exercise to produce important details, as architects become more accustomed to working with CAD/CAM or file-to-factory workflows (Willis & Woodward, 2010). This process is forcing architects, engineers and builders to “throw away the rule book” and rethink how they approach workflow, the presentation of data and the sharing of ideas (Chaszer & Glymph, 2010, p. 88).

THE EDFAB PROJECT

There is a good deal of research and development being conducted into large production systems in New Zealand, so the various EDFAB construction systems that have been developed target how automation can work with rather than exclude current SME building practitioners. The existing construction systems can be categorised into two groups that seek to exclude skilled construction labour. The first group, the community builders, naively place emphasis on the unskilled community volunteer, while the second group, the exclusive builders, seeks to bypass or diminish the role of the building practitioner. There is great risk with both approaches, as it can lead to problematic quality assurance and social issues.

The purpose of EDFAB, therefore, is not to propose a specific solution, rather to investigate what possible changes can be made to the building industry's existing ways of working through automation. It is important to understand that ease of access and digital literacy levels will differ between practitioners and would-be practitioners, so the investigation was geared around trying to show that automation is not so far-fetched or intimidating. Design parameters were created to test whether a product could be manufactured both by machine and by hand. This was done so design systems connect well with conventional construction processes to support and encourage adaptation among building practitioners. Various practitioners, researchers and students took part in three iterative prototypes, and guidance, engineering and technical support was provided

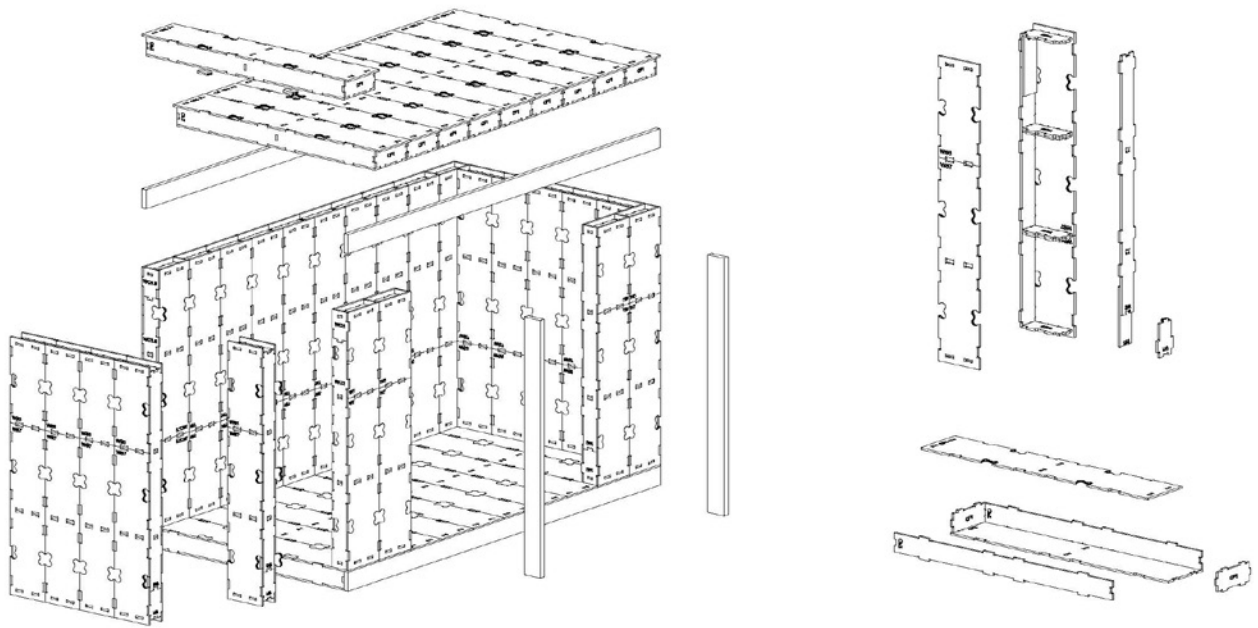
by lecturers from the University of Auckland and Unitec Institute of Technology. Each institution also supplied students from doctoral, masters and bachelor levels within their respective programmes to pursue iterative design and fabrication work. Industry partners such as Carter Holt Harvey and Pro Clima provided key technical support through their engineers and installation specialists, to ensure their products conformed to their code-compliant product statements. Lastly, practising architects and builders were constantly consulted to ensure that the outcomes would be realistic.

The EDFAB project underwent three phases: the first was based on a plywood-centric ‘kit of parts’ similar to the Facit Homes modular system. The second iteration was centred on reducing material waste and complexity by including laminated veneer lumber (LVL) in the construction system. The current and final iteration investigated the inclusion of portal frames to increase flexibility and participation of industry suppliers. While the first two iterations were important, they served to filter out inefficiencies and proposed solutions within digital fabrication-centric construction. The latest iteration, in contrast, sought to discover how off-the-shelf materials may be utilised without voiding the product specification guidelines provided by the material supplier.

The iterative prototypes involved failures that needed to be resolved with the help of the experienced builders, specifiers and engineers within the factory and onsite. The reality is that automated construction is not as simple as designing, printing and assembling. There is a need for experienced, skilled designers and builders more than ever to resolve issues that software and design cannot tease out.

EDFAB 1.0

Discussion between the collaborators was centred around producing numerous scaled, digitally-produced prototypes. A variety of laser-cut mock-ups at 1:5 and 1:10 scales were produced to test assemblages, while a series of full-scale mock-ups tested the CNC processes, connections, tolerance and materiality. The final mock-up was an inhabitable sleepout that was



EDFAB
DESIGN.BUILD.DELIVER

PROJECT: EDFAB PROTOTYPE - WHAU ARTS FESTIVAL

PLAN & SECTION

NOTES:

NOT TO SCALE

PAGE:



Figure 1. Above: The EDFAB 1.0 construction system.
Below: The process of fitting the modules into position
and locking them into place with the 'butterfly'.



Figure 2. The community engaging in construction of the EDFAB 1.0 prototype at the Whau Arts Festival, October 16-19, 2014.

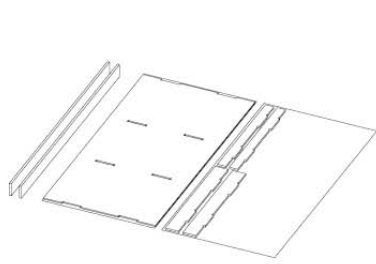


Figure 3. Smartfit window being installed, and the EDFAB 1.0 prototype completed on September 23, 2015, at a private residence in Manukau.

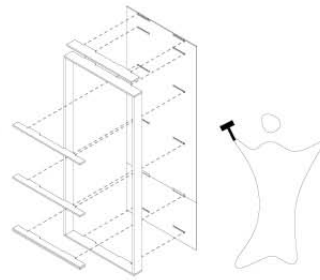
showcased at the Whau Arts Festival. Among the learning outcomes from this project was that it involved too much specification material and over-complicated joinery, which included ‘butterfly plugs’ to tie modular panels together that could easily have been replaced with the simple use of screws. The successful integration of products such as Fletcher’s Smartfit windows, Knauff’s Jet Stream insulation and Pro Clima building wraps proves that innovation can add value to the existing landscape rather than just disrupt it.

The EDFAB 1.0 prototype became a case study for the newly developed Smartfit window system, a perfect example of a mass-produced product fabricated by CNC production systems. The system

required product statement documentation to be procured through product suppliers or be generated by engineers to confirm it could meet the New Zealand Building Code requirements. The product comes complete and ready for installation, with no loose parts. Everything from the window flashings to the sill support bar are integrated into the window, allowing for reduction in human error and time during installation. The Smartfit window was fully fitted and sealed on the 1.0 iteration within approximately ten minutes.



Step 1.



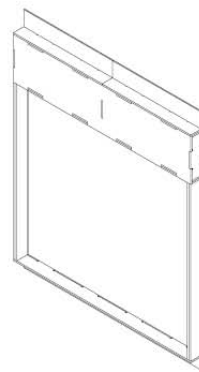
Step 2.



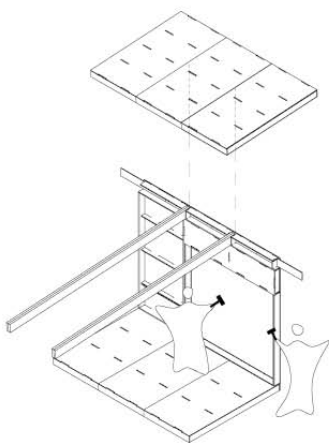
Step 2a.



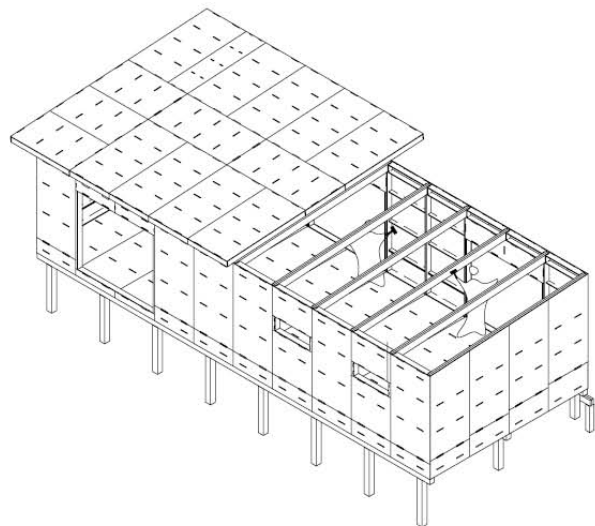
Step 2b.



Step 2c.



Step 3.



Step 4.

Figure 4. The assembly system of the EDFAB 2.0 prototype.



Figure 5. Left: Flat-pack components being fabricated at University of Auckland on a CNC router. Right: The EDFAB 2.0 wall-to-ceiling prototype at the University of Auckland, November 11, 2015.

EDFAB 2.0

The purpose of the second phase of EDFAB was simply to tease out inefficiencies in the previous iteration. The majority of the amendments were centred around the modular panels, where two major design faults were found. The first issue was with the 'Lego' system, where plywood boxes were placed and stacked upon one another. Each panel was 450mm wide, with heights or lengths at either 2400mm or 3000mm. The second issue was with the specification, and its inability to act as a weather-tight, rigid air-barrier, necessitating the use of an external building wrap. The updated design sought to efficiently use a more suitable plywood in conjunction with LVL to ensure structural, seismic and wind loading was allowed for. Ultimately the new approach led to CNC milling and assembly time being reduced by one fifth.

EDFAB 3.0

The latest phase of the project involved creating a system to push for greater inclusion of modular technologies and flexibility. The design exploration predominately investigated how portal-frame structures and simple CNC-produced modular

plywood boxes can cater for change and mass customisation.

Exposure of industry players to the EDFAB approach came with the 'Prefab NZ Interactive Display, Brought to You by Unitec' exhibit that was showcased at the BuildNZ/Designex expo at Auckland's ASB Showgrounds in June 2017. The prototype to be presented at the expo had to be a feasible product and showcase collaboration between the building-supply industry, workshop technicians, and female architecture and construction students from Unitec Institute of Technology.

The programme was split into three distinct segments within a six-week timeframe. The first four weeks were dedicated to design and documentation, while the fifth and sixth weeks were scheduled for material procurement and workshop fabrication respectively. The last day of the programme was dedicated to transporting the prefabricated modules from the workshop to the expo for assembly.

The design period of the programme allowed for the production of a scaled mock-up (Figure 6) to be produced. The exercise afforded the

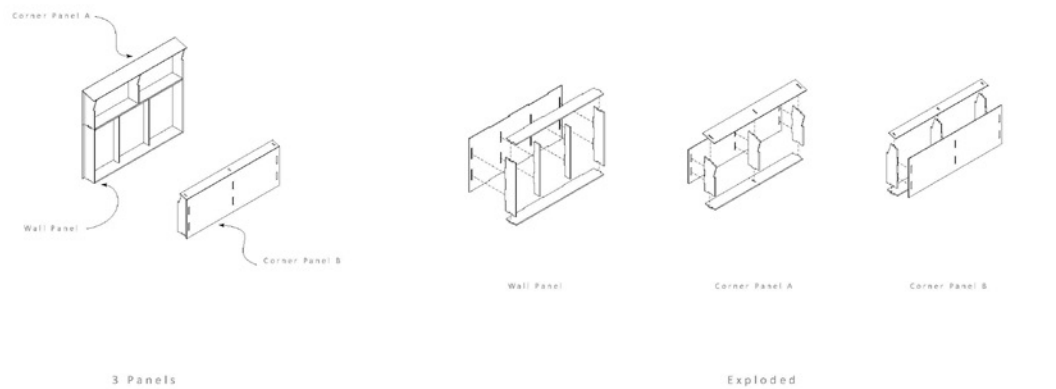
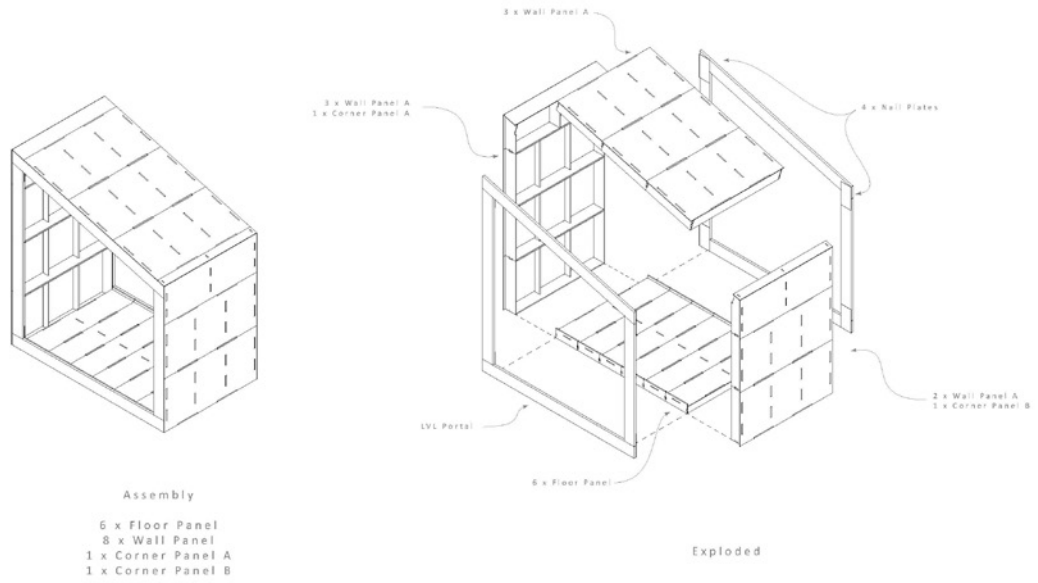


Figure 6a. Preliminary full-scale diagrams.



Figure 6b. The mock-up produced at Unitec, June 2017.

collaborating industry partners the opportunity to assess and refine structural connections, detail and viability in the incorporation of off-the-shelf products to the manufacturer's product specifications. It was vital step in the design development, as the application of all products needed to satisfy their respective BRANZ and Codemark technical appraisals.

All the designed elements were required to be made from products that could be bought from a major building-materials supplier, to ensure materials were readily accessible. The exception to the rule, however, came with Apex's modular wiring system and the custom laser-cut nail plates. The only other digitally-produced elements were the CNC plywood components that were assembled together to form the individual floor, wall and roof modules that infilled the space between LVL portal frames. Every other stage, such as assembly of the components into modules and cutting the LVL to length, was completed with conventional manual processes. Even though automated technology supplemented the limited construction skills the students had, it was important that a highly experienced builder was present throughout the build to ensure problems were resolved efficiently and products were installed correctly.

On the assembly day, the entire prototype was put together in one and a half hours. The onsite assembly allowed the team to determine if virtual measurements can dictate the actual fabrication

of the Smartfit window and its corresponding wall modules. This innovation allowed the window to be ordered once the window size was established in week four, well ahead of the fabrication of the wall modules. This is in contrast to the time-consuming conventional method whereby the window is ordered after the opening has been made, to ensure a correct fit. The time-saving approach trialled allowed the window to be ordered at the same time as the wall modules and for it to be fitted on assembly day without a problem.

After the exhibit was completed, the prototype was tested for volumetric modular transport to determine if it could be suitable for large-scale factory output and distribution. The prototype was moved to two locations successfully without any damage.

FINDINGS AND FUTURE RESEARCH

The design of the EDFAB construction system required everyone involved to be both designers and fabricators, and to reflect on past experiments so the design recipes could be developed and improved. The latest EDFAB 3.0 iteration is illustrative of how multiple technologies can be combined without too much difficulty and produce an effective solution for the future. The *Women in Construction* exhibit also was the first EDFAB prototype to be built by people – students and tradespeople – outside of the research team, within a six-week design-to-fabrication timeframe. The observations present the encouraging finding that it is indeed possible for individuals ranging in experience and skill to easily learn, fabricate and assemble a functioning prototype within a short period of time.

The research conducted by the EDFAB team was intended to provide new ideas to spark change in mainstream practices and discourse. The prototypes were not designed to be implemented by building practitioners at this stage, but to explore what is required from industry and to provide recipes to build upon – and are in this respect similar to the way the Wikihouse community works. Findings revealed that the greater the degree of integration between the contractor and the architect or designer, the better

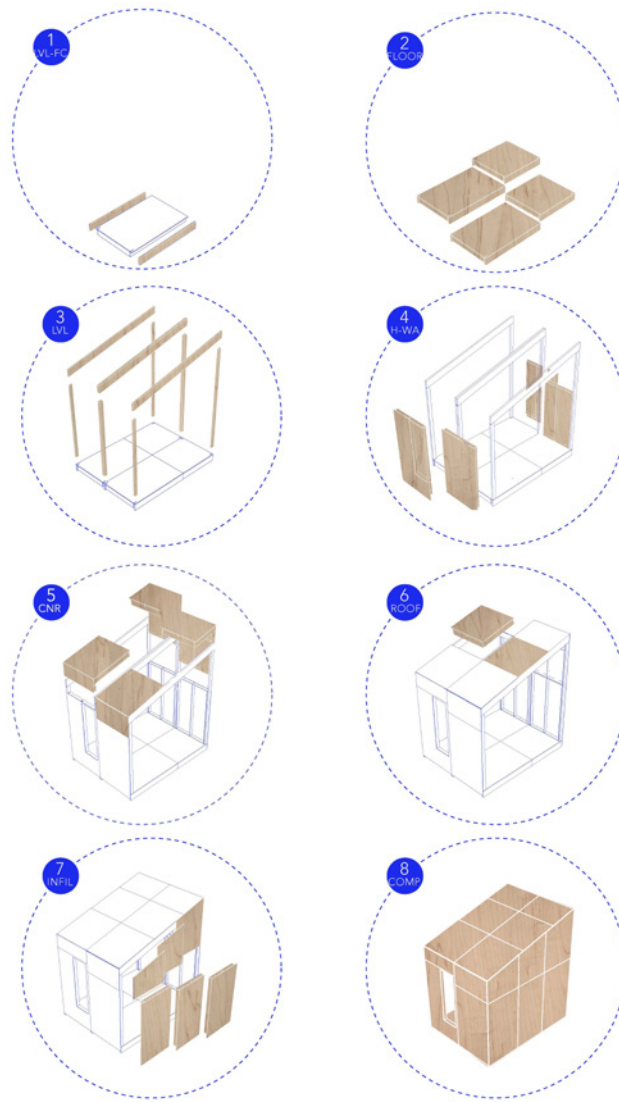


Figure 7. Above: The final construction system. Below: Final prototype at Designex/BuildNZ expo at the Auckland Showgrounds on June 24-27, 2017

the result. The EDFAB researchers relied heavily on a digital workflow to create meaningful and productive dialogue that can occur in the design and fabrication stages of any iterative prototype. By the time of the EDFAB 3.0 iteration it was expected that contractors or fabricators would be knowledgeable in the CAD/CAM process, and that the designers would be well-versed in fabrication logic.

The research team emphasises that digital literacy is a necessary skill-set element for current and practising building contractors in order to access automated processes. This is not an easy task, as it requires seasoned builders to integrate new steps into their accustomed workflow. The 4.0 iteration will investigate how the skills and knowledge of the experienced builder can be capitalised upon and developed, rather than their role being diminished or replaced on the construction site. Elements that concurrently need to be analysed are determining the quantifiable costs of labour, material and performance factors such as thermal comfort levels and energy efficiency. A major shortcoming of the iterative prototypes is that their size doesn't allow the opportunity to reflect upon the regulatory consenting process. Building in New Zealand requires this to take place, so a large enough prototype needs to be produced to test under such conditions.

CONCLUSION AND RECOMMENDATIONS

The advantages of prefabrication are well known to developers, councils and clients, and its potential is generally undisputed – benefits include greater safety, construction quality, time efficiencies, production consistency, cost savings and waste-material management (Smith, 2010). However, most of the examples presented in the international literature tend to consider large-scale operations and high levels of standardisation rather than attending to the SMEs that make up the bulk of the construction industry in New Zealand.

Digital technology is undoubtedly forcing industry to reconsider how they may approach prefabrication, and wider participation is a result. There is simply no excuse for ignoring

the opportunity for greater collaboration and for SMEs to take part in the revolution. There need to be more innovators emulating the systems such as those developed by Facit Homes or Makers of Architecture. Digital technology provides the means for many more people to take part in planning, design and production, and for the process to be highly organised – ideally, no construction should take place before everything possible can be quantified down to individual screws and construction time. Working in this way will lead to lean production-to-assembly process which yield reductions in transport, waste, storage, loads on infrastructure, and disruptions to the building process.

In order for industry to adopt and gain the benefits of automation, architects, engineers and builders are required to blur the lines that define their roles in the construction of homes. Contractors need not only to be familiar with CAD/CAM capability, but also to be well equipped with conventional construction knowledge and have the skills to cope with challenges that cannot be anticipated in a computer-generated model. Designers need to be well versed in fabrication logic, not just to be able to produce tangible digital production files, but also a range of well-produced 2D drawings to service the large proportion of contractors who are not well versed in the 3D realm. The fact remains that even in the presence of digital technologies, complex design requires considerable skill and expertise.

Ultimately, as an industry, our long-term goals should be education, while, in the short term, we should be trying to maximise what options are available to provide access points and economies to the industry. The research suggests it is possible to integrate current construction materials, processes and techniques into practice, but that the greatest barrier to uptake of automated prefabrication technology is with education and code compliance. Within the educational realm, if secondary schools understand the need to pursue the teaching of laser cutting and 3D printing, it is about time our tertiary construction programmes caught up and did the same, supporting students to learn to use fabricating software and to run digital fabrication machines.

The absence of building guides and codes for automated construction requires architects and building contractors to work through an expensive and time-consuming regulatory approvals process to achieve building compliance. This barrier hinders small businesses in gaining the benefits of innovation with automated processes. Industry, government and institutions need to provide incentives for research, and for the information to spread to everyday builders in the form of productive new rules, guidelines and codes that can positively disrupt industry practices.

Automated prefabrication methods offer a variety of new and innovative options to architects, builders, clients, developers, and council to benefit the urban and construction landscape. Software can allow designers, fabricators and installers to all quantify and measure the cost of building more accurately. The same technology could also provide a virtual documentation system that allows regulatory approvers, building inspectors and maintenance managers to keep track of changes throughout design, construction and post-occupancy stages of a building's lifecycle.

Prefabrication automation can provide the everyday consumer with an efficient, well-planned and measurable service, where the design-to-construction development is tailored to meet their needs and budget. It also presents an opportunity for design and construction enterprises on a variety of scales to collaborate profitably and creatively for all concerned. Local communities would also benefit from build-times that are less disruptive and shorter, making new housing available when and where it is needed more responsively and efficiently.

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