EDFAB: IS A DIGITAL REVOLUTION POSSIBLE FOR THE CONSTRUCTION INDUSTRY?

DERMOTT MCMEEL, JOHN CHAPMAN, MANFREDO MANFREDINI, PAOLA LEARDINI, GARY RAFTERY, YUSEF PATEL

The University of Auckland, New Zealand

ABSTRACT

As the noise and furore surrounding digital fabrication dissipates, where do we as designers and builders find ourselves? Contrary to media hype there is not a factory in every garage, nor are designers and builders becoming unnecessary. On the contrary, new models of manufacturing are emerging and new ways to design are developing in other industries where these innovations are not only profitable but radically improve the consumer experience. With early adopters well seasoned and leveraging benefits from digitally sponsored fabrication, where does this leave design and construction? In this paper we outline EDFAB: eco-digital fabrication, a research project partly funded by Transforming Cities: Thematic Research Initiative (TRI) of the University of Auckland, to develop new consumer-friendly forms of design and timber construction. The aim of the project is to challenge conventional processes and relationships, proposing radically new viable design and building alternatives that address problems of affordability, space adaptability, energy performance and indoor comfort. To do that, the project develops a system that introduces both process and product innovation. It combines enhanced construction technologies, new materials and digital fabrication methods to produce distinctive, high quality, healthier and cost effective residential buildings that conform to the international Passive House standard. The paper discusses the specific contribution to the project from the different involved research areas – building technology, architecture and sustainable design, and digital fabrication – and presents the early achievement of the research: a $10m^2$ prototype domestic scale 'sleepout', designed and built using digital fabrication, and novel plywood construction methods that produce a kit-of-parts very easy to build and handle. Easy to use software that enable consumers to tailor their designs and an expert interface that automatically creates the building components, that will permit the delivery of site-specific comfortable and energy efficient solutions are being developed. Contrary to popular myths, the research points to material skill and traditional craft and knowledge being more important than ever in the imminent digital revolution for construction.

KEYWORDS:

Digital Fabrication; Passive House standard; Prefabrication; Software

INTRODUCTION: REVOLUTION… AGAIN… REALLY?

Technology is synonymous with revolution, from machines of war to the industrial and information revolutions; technological innovation and disruption go hand-in-hand. The design and construction industry is no stranger to this, the industrial revolution shaped processes that would have a marked effect on the industry and more recently computers, CAD (computer aided design) and BIM (building information modelling) bring with them a wave of changes and transformations for construction. Novel forms of fabrication, made possible by these new technologies and processes, feature heavily in the literature. Prefabrication and its many incarnations hold promises of efficiency and productivity gains, although the potential benefits often suffer with widespread perceptions that choice and individual tastes have to be surrendered.

The aim of EDFAB is to take a fresh look at the situation and draw from current trends in consumer culture; from Amazon to iTunes other industries have been transformed by technology. While a single innovation often serves as a catalyst for these transformations, they eventually combine and automate other pre-existing resources to increase efficiency, choice, accessibility or ease of use. As the sector ecology transforms as a whole it become more competitive and productive, capitalising on efficiencies elsewhere and automating transactions through business-to-business services.

EDFAB looks at current innovations in digital fabrication and explores how other aspects within design and construction processes might capitalise on these efficiencies. What parts of the design and delivery process be automated or integrated? How will such a transformation impact skills and knowledge practices? Where can opportunities for near-term and long-term gains be found?

EDFAB: RETHINKING DESIGN TO DELIVERY

EDFAB (eco-digital fabrication) is a research project funded by the University of Auckland and its Thematic Research Initiative 'Transforming Cities'. The project is trying to answer some, or parts, of the questions that emerge as people and devices within the building industry become highly interconnected. Its aim is primarily to deepen our understanding of how changing technology alters skills, knowledge practices and processes within the building sector. Also, with the help of industry, the aim of the project is to identify pathways, areas and aspects of digital fabrication that are likely to have a meaningful impact on the industry itself and on housing quality and/or affordability.

Digital Seduction

If some of the key anthologies on digital fabrication (Kolarevic and Klinger, 2008; Kolarevic, 2003) and its stakeholders are examined (Burry, 2010, 2005) a preoccupation with form becomes apparent. This is perhaps because digital fabrication most obviously lends itself to the production of complex form. The primary structural elements in the spectacular roof at Oslo Gardermoen airport, Norway are massive glued laminated timber elements in the form of airplane wings as shown in Figure 1. Such geometric complexity would be difficult to produce by manual techniques.

Figure 1. Complex structural geometry in timber engineering

However it now appears the next phase beyond the initial fascination with novelty must take place. As both professionals and students alike are becoming more familiar and desensitised to the seductive possibilities of digital fabrication, a new criticality is emerging, questioning the value and benefit of emerging tools and techniques. 3D printing has been receiving considerable hype in the consumer domain for many years, without it finding its 'killer application' just yet. Although some small houses have been constructed using 3D printing technology in China (Balinski, 2014), they bring to mind

Karl Marx (Marx, 1977, p. 379) exhortation that the potential of automation is not about prosperity, but about dehumanisation. Marx was referring specifically to the workers who are replaced by technology but we might also apply this critique to owners and occupiers that might end up residing in potentially unpleasant, highly repetitive mass-produced housing. Currently robotics are gaining ground rapidly in the architectural domain, with Gramazio and Kohler (2008) having been, for some time, at the forefront of innovation with robotics and, more recently, drone assembled architecture. Like CNC (computer numerical controlled) routers, these linear kinematic robots have been used in the high value manufacturing sector for some time and are finding new uses in the building and creative arts sector. Which brings us to our research and a burning question concerning digital fabrication technology: how can we critique its value when it has already been highly valued in other sectors? In 'The question concerning technology', Martin Heidegger argues:

Because the essence of technology is nothing technological, essential reflection upon technology and decisive confrontation with it must happen in a realm that is, on the one hand, akin to the essence of technology and, on the other, fundamentally different from it. Such a realm is art. (Heidegger and Lovitt, 1977, p. 35)

In which case the design and construction of a piece of architecture is well suited as a vehicle to critique technology.

Big things and small beginnings

The EDFAB project (Figure 2) began by proposing to build and test a small timber based unit using some digital fabrication techniques that we see emerging in Europe and North America. The aim was initially to test if such a system could conform to New Zealand standards, because the system had the potential to deliver some unexpected benefits. It was very easy to construct, consequently reducing highly skilled labour costs, while the high accuracy possible with digital fabrication was able to deliver a very thermally efficient building envelope. Because the system consisted of essentially repetitive plywood cabinets, it was possible to programme software to create them automatically. Using Rhinoceros and Grasshopper 3D modelling software it was possible to create a parametric description of our unit or 'sleep-out.' This software could automatically subdivide the unit into a number of parts and then automatically create the cutting templates that could be fed directly into a CNC router for fabrication.

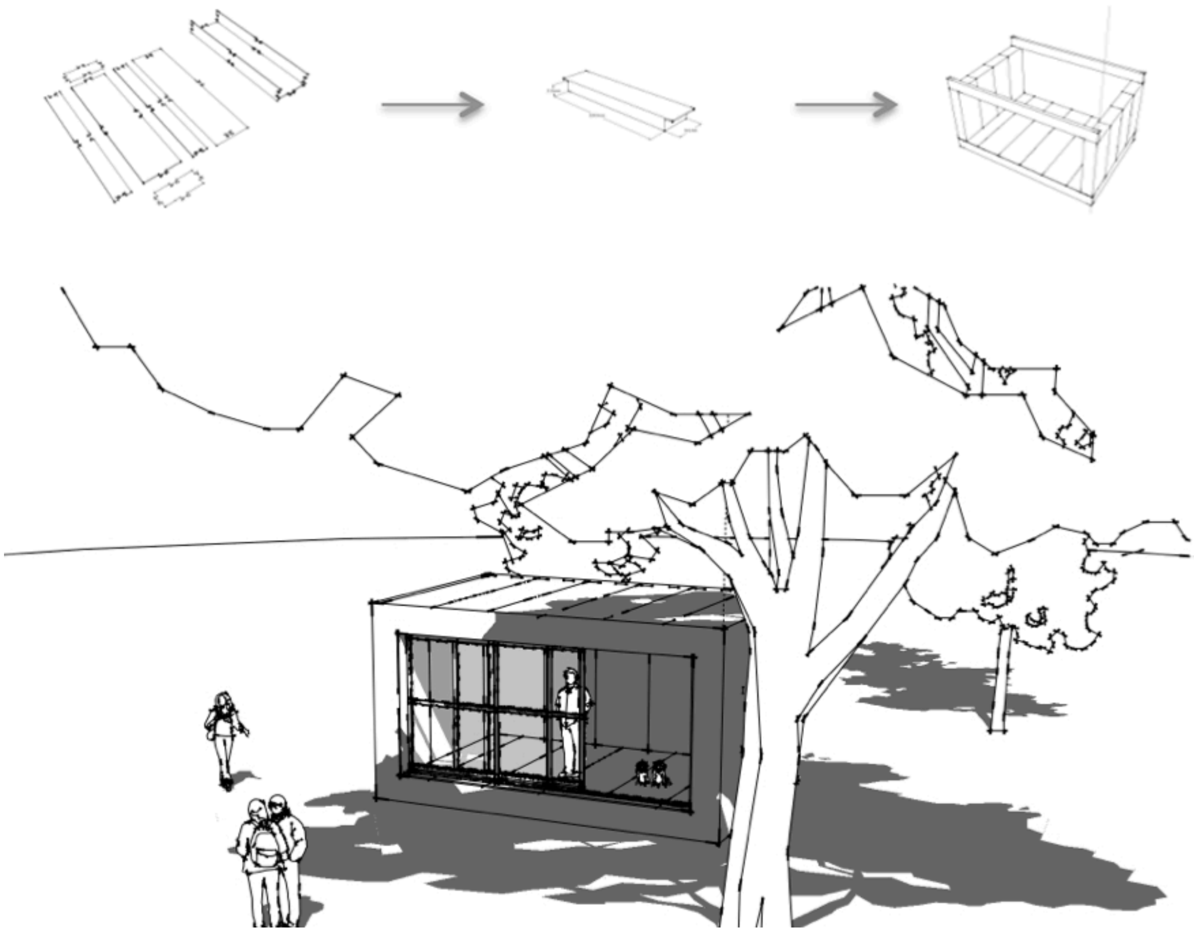

Figure 2. The EDFAB construction system to build a 'sleep-out,' a common addition to NZ domestic space

Through this process, constraints became opportunities. The depth of the unit was limited by the length of available plywood boards (2400mm) and the length was limited by the span possible using our chosen size of timber beam. By encoding constraints into the software, it was possible to prevent a user specifying dimensions that would create a situation where the unit could not be fabricated or, if fabricated, was structurally unsound. With these constraints encoded in our expert software, it became obvious that we could create a very easy-to-use computer desktop application that would enable a user to manipulate and tailor a unit's size to their specifications (but within the encode constraints). When a particular size was agreed upon, the information could then be communicated to the expert software that would then generate all the cutting component templates necessary. Making available a variety of customised solutions matching the pre-set constrains return certain freedoms to the end user (a client or prospective owner), freedoms that typically have to be carefully managed as they can easily delay or complicate a careful programme of design and construction. Traditional skills such as structural and environmental design expertise remained critical, but they could be shifted from the late design phase to the initial one, i.e. during the development of our software and data interchange protocols. New skills were also required in the form of software developers, in particular ones that were attuned to design and construction. For this stage of the project we were able to find them within the Department of Architecture, confirming what McMeel and Amor (2012, 2013) have discussed elsewhere, i.e. that the skillsets of emerging Architects increasingly involves programming abilities of varying degree.

Early questions

Having assembled a team of specialists from domains such as architectural, structural and environmental design, and software development, a number of provocative questions soon came to centre stage:

1. Does this digital fabrication work in the New Zealand context?
New Zealand Building Code differs in many ways from European and North American building regulations. In particular the system has been tuned to take into account the seismic activity and the potentially high wind loading. Buildings in New Zealand must be able to withstand twice the wind loading of buildings in England. Furthermore, materials and components currently available in New Zealand have different physical and mechanical properties compared to the same products manufactured overseas: plywood is such an example. This material could have been easily imported from overseas. However, a self-imposed criterion was to utilise local products where possible - for both environmental and economic reasons.
2. What constraints can we encode within the software?
As a consequence of using parametric modelling software - which will be explained in some detail in the following sections - we could quite easily impose constraints that ensure structural stability. Alternatively we could automatically alter the size of structural elements in response to a user creating larger spans. Returning to Heidegger for a moment, the fact that we can do this should not preclude asking why are we doing it and to what ends.
3. Where can communicating with digital data improve upon traditional techniques?
It is not always desirable or possible to automate; it is necessary to call upon expertise. Even when information is exchanged digitally it is often necessary to extrapolate from a complex model the specific information that is required by the specialist, taking both time and resource. In the event of a change this manual extrapolation has to be repeated for the expert to render a decision or service based on the new information. If we cannot automate a particular expertise can we automate data extrapolation, thus saving time and resources?

To help answer some of these questions, in the next section we will give a more detailed account of the process of developing the construction system as well as some end user and expert software.

COMMUNICATING: AU NATUREL

Communication is critical during design and construction. Paper drawings are a long established means of transferring information between the multitude of professions and trades necessary to deliver a finished building. Drawings have evolved into a very effective tool to communicate, coordinate and help disparate stakeholders converge on a common understanding. DWG (the proprietary file format of AutoCAD) and DXF (Drawing eXchange Format) are the digital equivalent and have been used successfully since the 1980s for exchanging geometry in the form of drawings and models. We are however in the Information Age where CAD (computer aided design) has given way to BIM (building information modelling). Geometric models have given way to information models and exchange formats such as DXF and DWG have give way to IFC (Industry Foundation Classes) and CoBIE (Construction Operations Building Information Exchange). These digital standards and conventions seem in keeping with their paper predecessor, but there is a stark difference. Whereas drawings are a means to mediate the different languages, grammars and ontologies that make up the building process, these emerging standards are languages of themselves and, although they are descriptively adequate to communicate between virtual stakeholders, they are neither particularly efficient or particularly optimal for communication between any roles or disciplines. McMeel and Lee (2007) have scrutinized construction ontologically and theorized an emerging pre-ontology, which provides a framework to conceptualize these communication conventions. Although they appear highly problematic and the industry's resistance to the uptake of these communication conventions is well documented. The notion of a pre-ontology, be it in the form of IFC or CoBIE, does not seem to have a natural resonance with industry stakeholders. Design and construction is—like nature—a competitive ecosystem where the fittest and leanest survive. There is no room for inefficient communication, no matter how comprehensive it is.

Let us turn for a moment to the natural world's complex ecologies and communication systems. Where one insect uses colour to fend a predator, another uses scent to attract a mate; they are specific and clear channels of communication. In *Life Itself*, Robert Rosen (1991), the theoretical biologist, has conceptualized this in terms of 'dictionaries.' Each channel of communication has two dictionaries associated with it, one at each side of the communication channel, for encoding and interpreting the signal. Rosen makes it clear these dictionaries are not necessarily the same, but they are highly efficient. As an ecology grows so do the number of dictionaries, but importantly they are quite simple. It is the aggregation of these channels that makes for a complex ecology. This is in stark contrast to communication within the AEC (Architecture, Engineering and Construction) industries, where best practice is often to implement a complex interoperability protocol, which is highly technical and somewhat overwhelming. It is perhaps then natural that they are resisted. In EDFAB we took a fresh look at communication and used Rosen's concepts of natural communication to inform our strategy. In this section we will detail the three parts of the project, the construction method, expert user interface (xUI) and the end user interface (eUI). We will discuss the parts of the EDFAB ecology and how the efficiency of the communication protocol was addressed.

Digitally sponsored construction

Exhaustive surveys of the impact technology has on human interactions in office environments have been carried out by Robert Kling (Kling and Iacono, 1984; Kling, 1980, 1996), an expert on the study of social informatics. One of Kling’s key findings, which we might take for granted today, is that where technology is introduced unexpected things happen. Often this is as a consequence of technologies’ effect on human interaction. Technology alters the ease or difficulty with which we communicate, skill sets need to change and roles become redefined. He also recognised that technology is sometimes implemented for political reasons, in such cases Kling found there is often little evidence that politically motivated change actually delivers overall improvements. Turning to construction, we have lessons that can be learned; firstly to exploit digital fabrication technology change is necessary and secondly these changes will likely have consequences well beyond the places they are implemented.

In the last ten years a method of construction has been emerging and documented (Bell and Simpkin, 2013) that capitalises on digital fabrication. This method has been used successfully by Facit Homes, a bespoke house design and manufacturing company in the UK. The system breaks a design down into building blocks; one might draw the analogy of a LEGO system for grownups. Each block is then broken down further into flat pieces that can all be cut out of standard sheets of plywood by a CNC router and easily assembled. The blocks are easily carried by two people and built up on site. The system was modified to accommodate the plywood availability and building standards in New Zealand. A 1:1 scale prototype of one section of the sleepout was built (Figure 3) to test the system, detailing and tolerances. This information will be built into the digital models and software interfaces to ensure some similitude between the digital model and the final real building. The system uses a ‘butterfly’ plug that is hammered into place between each block; this interlocks the blocks and creates a robust structure. In Europe the current best practice is to tape the joints in lieu of wrapping the structure in a vapour barrier membrane.

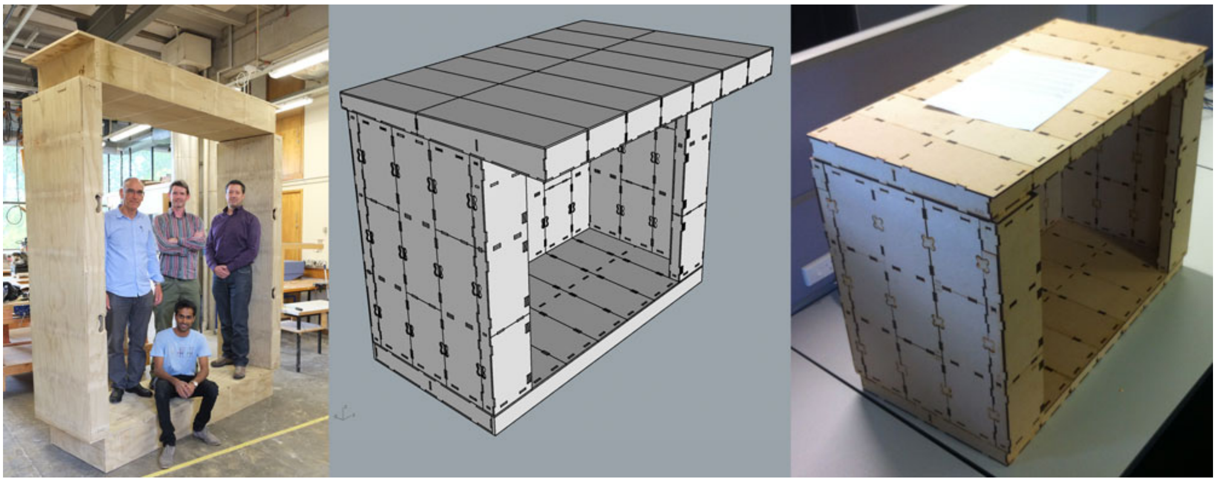

Figure 3. 1:1 prototype, digital model and 1:6 scaled model of the sleepout

During this process a number of factors emerged. Locally available New Zealand plywood for general building construction is not as dimensionally stable as its European counterpart; Latvian Birch appears to be the plywood of choice for this method of fabrication and construction. Indeed imported Chilean plywood was also used and also found to have deviations that cause problems for digital fabrication. Even with these stability issues it was possible to construct the 1:1 section. Having completed the section of the 1:1 model and modified some details, a 1:6 scaled model (Figure 3) was construed to assess the new details, the over all construction concept and also to check for 'creep', i.e. the phenomenon where small deviations in the physical construction are aggregated over the length of the building causing the combined components to be of a different length than intended.

xUI: Expert user interface

The expert user interface is closely linked to the construction technique, as much of what was learned through the building the prototype and model was necessary, as aspects of it would be encoded into the software interface. The interface is built using Rhinoceros (http://www.rhino3d.com/), a popular 3D modelling software, in combination with Grasshopper (http://www.grasshopper3d.com/), a parametric plugin that provides a 'procedural' interface for Rhino.

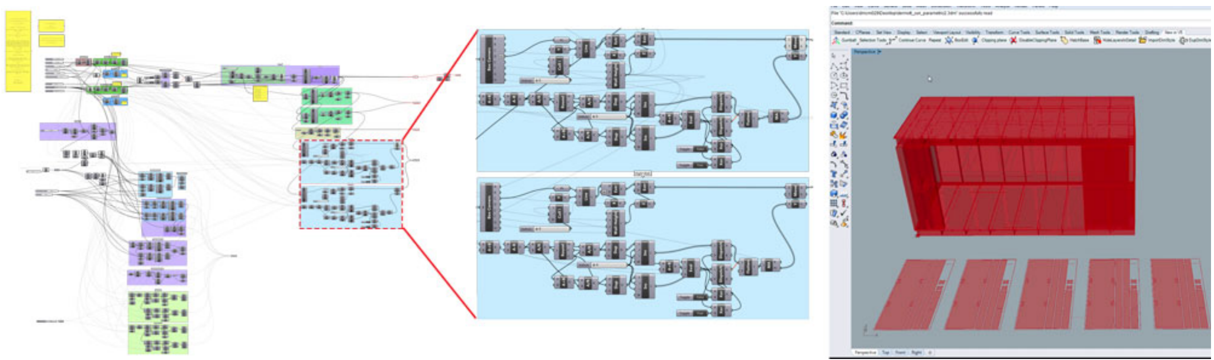

Figure 4. On Left the xUI Grasshopper description; Centre a detail of its complexity; On right a screenshot of the xUI building the model and its components

A sense of the complexity of this process can be gleaned from Figure 4. At the extreme left we have an illustration of the software, the centre diagram is a detail of its complexity - each box represents a calculation or decision. For example one of these boxes contains a detail drawing of our butterfly joint. If we decided to change the joint we could change the detail once and have it changed throughout the project automatically. The illustration on the left of Figure 4 represents only fifty precent of the software, which executed choices and decision based on what we have learned from building the prototype section and the 1:6 model. It is interesting to look at an image of what is essentially a digital encoding of the design decisions necessary to create the construction components from a 3D model. It gives us pause for though about the complexity of a typical design and construction process, where here there are literally hundreds of interconnected decision and choices necessary to deliver a relatively small and regular shaped building.

The only input the expert system needs is three Cartesian coordinates that represent the length, width and height of the sleepout. With the deepened understanding of the system we could impose limits on these dimension to ensure constructability and structural stability. With this in mind we commissioned a standalone easy to use application that could be downloaded by an end user to tailor their design requirements. Concurrently we were devising a communication protocol to exchange information between the end user interface (eUI) and the expert user interface (xUI).

eUI: End user interface

The end user interface (Figure 5) was written in C++, which was chosen because it can be compiled to run on almost any computing device, such as Windows PC, Mac OSX or handheld devices running the iOS operating system from Apple. None of the sophisticated construction information is replicated here. This is a simple application that gives the end user the visual appearance of the sleepout construction, and offers the ability to easily change some of the dimensions within the limits we have specified. A silhouette gives a sense of scale and there is an approximate floor area provided – a value that is useful to a potential end user. In essence, having worked through a processes to capitalise on digital fabrication and build software that enable us to leverage the benefits, we have been able to pass certain freedom, in this case design freedoms, onto the end user. These design freedoms are not afforded under traditional design and build processes as they have the potential to compromise the construction programme.

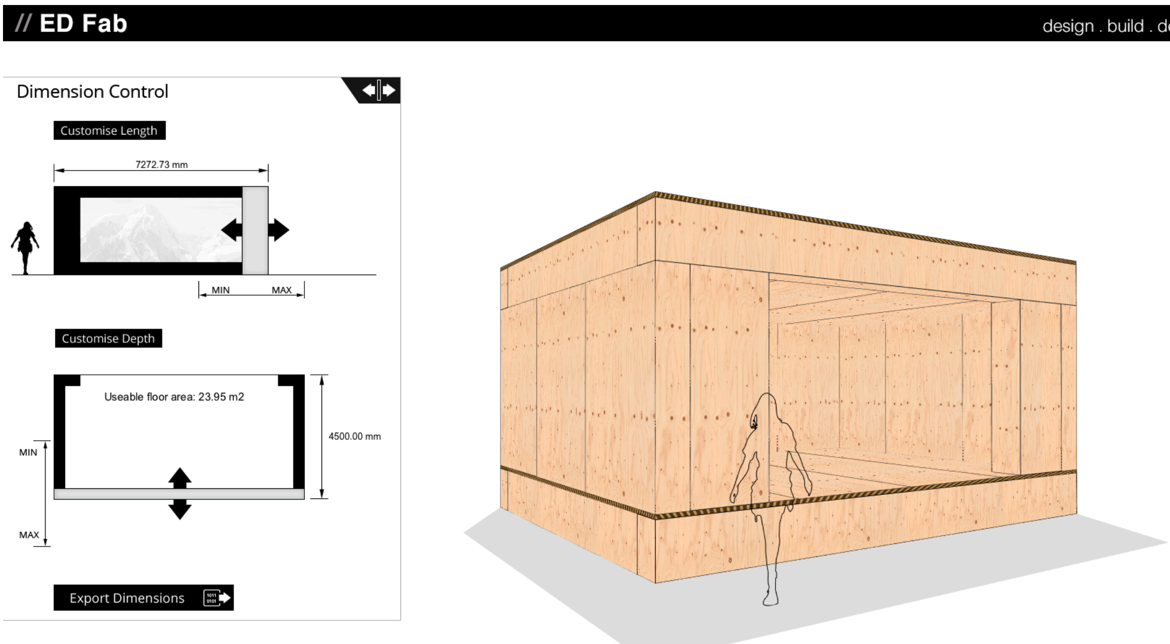

Figure 5. EFFAB end user interface software

Under a traditional design and build programme when the need for information exchange arises a geometric model interchange standard is used. Most of the standards for digital information exchange in the AEC industries are for communicating geometry (OBJ, DXF, DWG, 3DS). Within our ecosystem we have no need for communicating geometry. Instead, we need to send some coordinate information and the xUI will build the geometric model according to its needs, initially we explored IFC and CoBIE, which have been mentioned earlier in this paper. Both are very comprehensive but IFCs have a very complex syntax associated with them and CoBIE seems to privilege a spreadsheet layout, which is not optimal for application data interchange. We instead adopted a CSV (comma separated variable) file syntax, which has a very simple structure (Figure 6). This file type is quite common for transferring information to and from databases and subsequently is suited to both data exchange and to efficient digital communication.

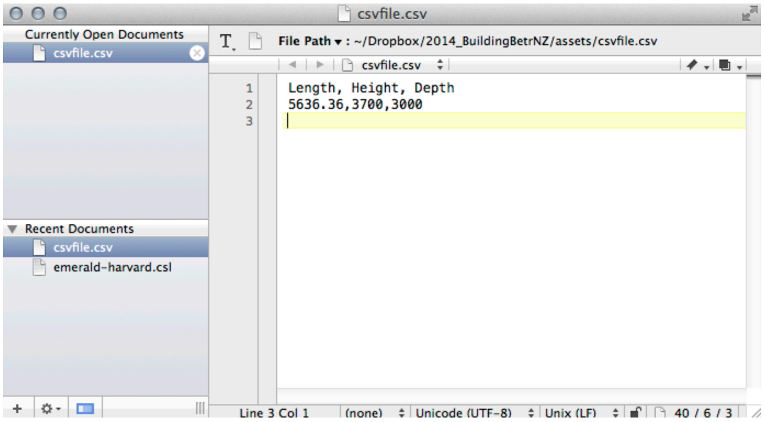

Figure 6. The CSV file for exchanging information between the eUI and xUI

This was the simple ecosystem we developed to leverage the possibilities of digital fabrication. It is still a work-in-progress and at the time of writing we are exploring the possibilities of further structural encoding as well as utilising JSON (Javascript Object Notation), a file type that is very popular for data exchange, particular in the burgeoning area of GIS (geographical information systems) and geospatial data, when vast quantities of data need to be transferred quickly and reliably.

CONCLUSION

This is a project that is modest in scale and scope, but has revealed a number of highly interesting factors. Traditional construction skill and structural knowledge remain critical, even within this extreme adoption and implementation of digital fabrication; people with these skills continued to be key parts of the team and the design development process. However compared to a traditional design and construction process their presence was more critical at an earlier stage.

Communication is critical, although for the projects initial needs, it was chosen not to implement a standard. Instead we asked ourselves what we need to communicate and why. That gave us a framework to scrutinise some of the options that were available. When a communication standard was implemented (CSV), it was from the IT industry not the construction industry. The IT industry has been wrestling with large datasets and communication for several decades and it is not unexpected that may have standards that we can utilise as we develop our own. Communication remains a critical issue and it is telling that many current successful BIM case studies involved integrating the team, often relocating the entire project team to a single unified location. There is still a lot to be understood about what and why information should be communicated, and perhaps taking our lead from the natural world, these channels and purposes should be clear and efficient.

Most interesting perhaps was the newfound freedom that could be passed onto the end user, the person or persons that might consume such a piece of architecture. When we see the entire construction and software ecology it is not dissimilar to music and book buying, where technology has changed the market from a supply driven to a demand driven one. Giving choice and power to the end user and taking it from corporations. Given that a home, for many, is the single biggest purchase they will ever make and environmental imperatives, including aspects such as energy efficiency, comfort and health, are too often translated in overwhelming set of rules (as they require expertise and cannot be managed by the end users) that necessarily affect the design freedom. In our system instead these rules are simplified and metabolised within the digital framework, ironically it might be digital fabrication and automation that is returning freedoms to the consumer.

ACKNOWLEDGEMENTS

This project was made possible with funding from Transforming Cities, a Thematic Research Initiative at the University of Auckland. Many thanks to Yusef Patel, whose PhD is supported by the BRANZ Building Levy, Sindre Johnsen, who developed the expert interface and Kent Van Velden, who developed the end user interface.

REFERENCES

Balinski, B. 2014, "Chinese company 3D prints 10 houses in a day from recycled material", Architecture and Design.

Bell, B. and Simpkin, S. 2013, "Domesticating Parametric Design", Architectural Design, John Wiley & Sons, Ltd., Vol. 83 No. 2, pp. 88–91.

Burry, J. 2010, "The Shifting Ground of Architectural Geometry", Architectural Theory Review, Vol. 15 No. 2, pp. 187–200.

Burry, M. 2005, "Digitally Sponsored Convergence of Design Education, Research and Practice", in Martens, B. and Brown, A. (Eds.),CAADFutures: learning from the past, Springer, Vienna, pp. 3–22.

Heidegger, M. and Lovitt, W. 1977, The question concerning technology, and other essays, Harper colophon books, Harper and Row, New York; London.

Kling, R. 1980, "Social Analyses of Computing: Theoretical Perspectives in Recent Empirical Research", Computing Surveys, Vol. 12 No. 1.

Kling, R. 1996, Computerisation and Controversy: Value Conflicts and Social Choices, Academic Press, San Diego, 2nded.

Kling, R. and Iacono, S. 1984, "The Control of Information Systems Developments After Implementation", Communications of the ACM, Vol. 27 No. 12, pp. 1218–1266.

Kohler, M. and Gramazio, F. 2008, Digital materiality in architecture, Lars Müller Publishers, Baden.

Kolarevic, B. 2003, "Architecture in the digital age - design and manufacturing", Spon Press, New York.

Kolarevic, B. and Klinger, K.R. 2008, "Manufacturing material effects - Rethinking design and making in architecture", Routledge, New York.

Lee, J. and McMeel, D. 2007, "'Pre-ontology' considerations for communication in construction", in Teller, J., Lee, J. and Roussey, C. (Eds.),Ontologies for Urban Development, Springer, Verlag, Vol. 61, pp. 169–179.

Marx, K. 1977, "Grundrisse", in McClellan, D. (Ed.),Karl Marx: Selected Writings, Oxford University Press, Oxford.

McMeel, D. and Amor, R. 2012, "Digital Ecologies: A shifting paradigm for construction", in Lin, Y.-C. and Kang, S.-C.J. (Eds.),Proceedings of ConVR 12th International Conference on Construction Applications of Virtual Reality, National Taiwan University Press, Taipei, Taiwan, pp. 460–466.

McMeel, D. and Amor, R. 2013, “Fabricate It, Paint It – And Don’t Wait up: Separating Fact from Fiction in Digitally Sponsored Fabrication”, in Zhang, J. and Sun, C. (Eds.),CAAD Futures, Springer Verlag, Berlin, pp. 149–158.

Rosen, R. 1991, Life itself : a comprehensive inquiry into the nature, origin, and fabrication of life, Complexity in ecological systems series, Columbia University Press, New York, p. xix, 285 p.