Author/s:
Colabella, S;Gardiner, B

Title:
Housing Prototypes, Timber Tectonic Culture and the Digital Age

Date:
2019

Citation:
Colabella, S. & Gardiner, B. (2019). Housing Prototypes, Timber Tectonic Culture and the Digital Age. Bianconi, F (Ed.). Filippucci, M (Ed.). Digital Wood Design Innovative Techniques of Representation in Architectural Design, Digital Wood Design Innovative Techniques of Representation in Architectural Design, (Academic), 24, pp.911-935. SpringerLink.

Persistent Link:
https://hdl.handle.net/11343/336090

# Housing Prototypes, Timber Tectonic Culture and the Digital Age

**Colabella Sofia and Gardiner Blair**

**Abstract** Arguably the balloon frame exemplifies the commencement of the embedment of structural performance within timber construction standardisation and a system innovation responding to socio-technical issues in domestic construction. Three recent residential architecture prototypes which embrace digital design to fabrication are discussed as continuing this tradition. Held as exemplars of the capacity potential of digital design to file-to-factory these projects offer an opportunity to reflect on questions related to material culture, the social networks of construction and the boundaries between architecture, structure, materials, and construction. This chapter raises a series of discussion points centred around the role of timber-based products, in a digitally enabled domestic construction industry.

**Keywords** Housing prototypes · Digital design · Timber innovation
Digital fabrication · Tectonic culture · CAD/CAM

## 1 Introduction: Fast Wood in the Modern World

Timber, arguably the second-oldest material worked by the human hand, after stone, has been used as one of the necessary building materials for millennia. It, therefore, has an embedded history with architecture especially in the development of domestic architecture. Its use derives from locally sourced species, autochthonous cultures, traditions, experiences and skill sets. These broader characteristics have influenced specific regional forms of domestic timber building (Dangel 2016). Its historical, social roots lie with carpenters responsible for developing a comprehensive design that united the roles of the architect, structural engineer, and fabricator in one person. After essential design features had been agreed upon with the client, the carpenter

C. Sofia (✉) · G. Blair
Faculty of Architecture, Building and Planning, Melbourne School of Design, Parkville, Australia
e-mail: s.colabella@unimelb.edu.au

G. Blair
e-mail: b.gardiner@unimelb.edu.au

 
F. Bianconi and M. Filippucci (eds.), *Digital Wood Design*, Lecture Notes in Civil Engineering 24, https://doi.org/10.1007/978-3-030-03676-8_37

followed customary rules of practice for selecting the type of construction, determining the building's geometry, and developing the details. The work of the carpenter pointed to the overall composition and proportions rather than precise measurements, which resulted in no two structures being precisely alike (Dangel 2016). Industrialisation saw a shift in this mode of production which fragmented the process to increase production efficiencies and establish a division of labour (Pfammatter 2008). Industrialisation also contributed to the development of new timber-based products, which have given rise to structural systems and use that go beyond the limits of traditional wood construction.

Setting aside the licit doubt on the real sustainability of harvesting trees, the use of managed forests as the source of certified timber products has gained normative acceptance. The use of global certification schemes, exemplified by the 1993 Forest Stewardship Council—FSC, and Programme for Endorsement of Forest Certification, has widened from protection of forests to the incorporation of the social, economic, and cultural implications that arise from the commercialisation impacts of timber (Falk 2005). The preserve of this mindset is supported by the use of renewably harvested softwoods and its application in domestic construction arising from supply capacity maintenance in those industry sectors, historically embedded to the timber frame, and its continued relevance in contemporary labour markets interest in low skilled assembly techniques.

The advent of digital tools, it is purported, offers the capacity to continue the transformation of the timber tradition and its application in the domestic construction sector. These influences range from design conceptualisation to advanced applications which combine and integrate architectural and structural engineering perspectives. Digital working methods, such as CNC machines and associative parametric modelling, have entered the shop floor, but some have highlighted that they are not a wholesale replacement for what came before them (Smith 2008).

In this chapter, the interest in the continued relevance—in the digital age—of timber as a housing material of choice is interrogated as are the implications of digital design to fabrication in the residential construction sector. Tracing the balloon frame as exemplifying, in the modern age, the commencement of the interest in the embedment of structural performance within timber construction standardisation, three recent examples that develop this interest through the digital design-digital fabrication nexus are discussed. The first two have been chosen in the context of the MoMA exhibition 2008 entitled 'Home Delivery: Fabricating the Modern Dwelling', curated by Barry Bergdoll and Peter Christensen: (1) 'Burst*008' beach house, designed by Jeremy Edmiston and Douglas Gauthier; (2) the 'Digitally Fabricated Housing for New Orleans', from the MIT School of Architecture and Planning guided by Professor Lawrence Sass and (3) 'WikiHouse', an open-source project developed by Alastair Parvin. The three have all been held as exemplars of the extent digital design can offer a chance to cross the boundaries between architecture, construction and structure by offering tools for the customisation of the components and the control of the constituent components. They have also been put forward as being at the forefront of successful models of digital design and digital fabrication in the use of timber-based materials, geared to low-cost, low skill labour use as a transferable housing solution.

A series of questions arise, though not necessarily answered.[1] Do digital tools represent true innovation in timber building or just another iteration? Do digital tools integrate design and making, craftsmanship and structural compatibility for a material historically connected to these modes of production? Do such tools offer the opportunity to reconfigure links in the construction supply chain and offer the designer to actively engage in the making of buildings and the makers of buildings engaging with the conceptual design of them? Do digital tools offer unprecedented access to intellectual capital and information exchange which facilitates permeation of capacity building access via a construction material which has traditionally circumvented formally driven social structures?

## 2 Tectonic Culture in Timber Architecture: From the Industrial Revolution to the Engineered Timber

Innovation may be described as a non-trivial change via an improvement in a process, product or system to the entity introducing the change (Freeman 1982). A selected example of these forms of innovation in the 19th and 20th century suggests that changes to a ubiquitous construction material as timber has the potential for significant and widespread impact if picked up and applied due to its embedded nature within the industry as a whole. However, to do so effectively, certain conditions need to be met which are related to the structural conditions and frameworks which are unique to the construction industry.

The industrialisation of timber production offered an alternative to the architecture of heavy timber components, which prescribed a careful fitting of components through complex joinery (Dangel 2016). Amongst the most significant innovations in timber construction, whether attributed to George Snow or Augustine Taylor (Sprague 1981) in the early 19th century, were the development of the balloon frame and its refinements in the platform frame and panel-braced frame. Facilitated by the advent of the steam-powered circular saw, which made boards and small wood framing members inexpensive and readily available, and by the industrial mass production of cheap nails (Dangel 2016). This innovation responded to the demands of territorial expansion and development, dictates of timber scarcity, and permitted the use of unskilled labour and minimal use of specialist tools.

Due to its flexibility, the speed of erection, and low cost, platform framing prevails as the most commonly used construction type for residential and small-scale commercial buildings in many parts of the world. The further refinement of this form

[1] As Mario Carpo argues in his book "The Alphabet and the Algorithm" (2011), indeed, 'Technologies change rapidly "new" technologies in particular. To predict, and even interpret, new developments in cultural technologies on the basis of their recent history is risky, as one needs to extrapolate from a curve that is too short and build on evidence that has not been sifted by time'.

of timber construction has not arisen due to the system but due to other pressures which impact developed economies. Amongst these is the cost of construction project financing which has led to solutions that are geared towards the reduction of the construction program. Equally important is the cost of on-site labour and the reliance on competitive subcontracting which are quick to adopt solutions that reduce on-site labour time. Hence, we have seen the fragmentation of the supply chain through the rise of prefabricated timber framing systems and the demarcation of factory-based and on-site labour. This potential has applied to the constituent parts of the building but has failed to develop the early 19th century's interest, through timber and steel prefabricated housing as a response to colonisation and 20th-century examples of mass consumption such as in the 'Sears Catalog Homes' in expanding it to the building as a whole.

The early application of the balloon frame such as George Snow's warehouse building (1832) and St Mary's Church both in Chicago (1833) has been argued as arising from a response to the demands of rapid urbanisation, accessible timber resources and a shortage of skilled carpenters. The design response was for the systematisation of the use of scantling timber and nails as the primary connecting method (Sprague 1981). Since Giedion's interest in this form of construction (Giedion 1941), the balloon frame and its development have been seen as being the most influential innovation in timber construction Over time, this system became fully industrialised; whole houses came to be packed and shipped as a kit of numbered pieces for fast and ease of assembly. The invention of the balloon frame, and its development into the 'Platform frame', using one story high studs, has also been claimed as the antecedent of the skyscrapers. Pfammatter suggests that they hold a common structural analogy and arise due to common spatial and economic demands (Pfammatter 2008). However, fire regulations in response to the 1871 Chicago Fire, new processing techniques for iron, steel, and concrete, as well as the appearance of a new architectural typology, confined timber to a marginal niche of low-cost material for small residential buildings.

The invention of glued laminated timber channelled a significant upturn in timber construction beyond the confines of domestic construction. The acquisition in 1906 by Otto Hetzer, a Weimer master carpenter, of a patent for the production of beams composed of a number of lamellas glued under pressure, allowed Hetzer to develop a new method of timber construction. By using smaller sections and less structurally refined wood, this new material unbounded the selection of timber from the dictates of species and trunk size and heralded a widespread use of engineered timber construction. Hetzer's patent was further developed into the 'Glulam' product which has become a staple response in contemporary long-span timber applications. Hetzer's invention revolutionised the use of timber and offered an apposite, predictable, and reliable transposition; it eventually led to the further evolution of a large set of engineered timber-based products. Glulam, allowed the separation of the structural components from the spatial enclosure, expanding the possibility of plan design and, by doing so, competing in a niche traditionally dominated by concrete systems (Falk 2013). However, the output still replicated traditional formal architectural expression and took time to percolate through the strata of building typology, eventually serving

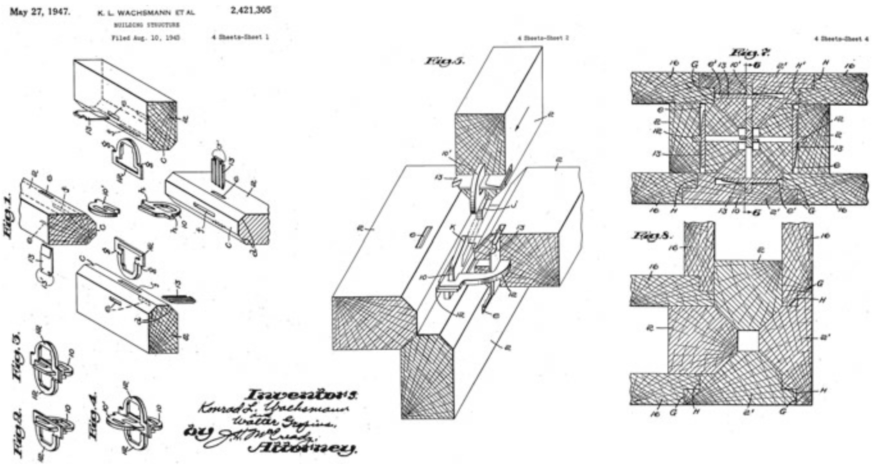


**Fig. 1** Patent 'Building Structure' used for the General Panel System, No. 2,355,192, granted to Konrad L Wachsmann and Walter Gropius on August 8, 1944. From left to right: sheets no. 1, 2 and 4. *Source* Google Patents [online]. Available at: https://patentimages.storage.googleapis.com/74/c5/31/093da0152d79c0/US2421305.pdf

as major load bearing elements in domestic buildings rather than as a complete system of construction. Further iterations of timber-based products, such as plywood, allowed the evolution of light frame constructions into the panel construction system.

In 1941 the German emigre architect Konrad Wachsmann revisited his earlier involvement in the design of prefabricated wood houses by collaborating with another United States emigre, Walter Gropius to develop the 'General Panel System'. Wachsmann and Gropius's 'Packaged House' system sought to advance wood-frame, panelised houses into a mass-produced industrial product as a response to wartime demand (Herbert 1984). The idea lay in developing a modular timber-based building system which was three-dimensionally symmetrical where it was possible to form any combination of connections in any direction (Fig. 1). Despite a factory geared for production of 10,000 houses per day, significant investment by the US National Housing Agency, a combination of malfunctioning equipment, Wachsmann's punctilious nature and a lack of opportunistic sales and marketing skills contributed to sales of just fifteen houses by 1948 (Davies 2005).

The 'Packaged House' is a telling reminder of the risk and degree of intellectual and capital investment required in developing a system of timber construction that lies outside the normative operative system of the construction industry. A timely solution to the unique dictates of wartime demand took too long to respond, by the time it could, the normative operative system of the construction industry fell back to overwhelm the potential of the widespread application of timber prefabrication as a housing solution.

The industry adopted Hetzer's 'Glulam' invention as it could be integrated, by substitution, into an existing already established system of residential construction.

The ‘Packaged House’ did not as it asked the industry to change the system. The balloon frame represents an interesting study of construction innovation as it established a different architectural paradigm (a rhythm dictated by ready-made timber framing members, carrying an equal distribution of the building’s vertical compressive load) concealed into a recognisable shell, indifferent to the rhythm of the structure. Most of all, the invention of balloon framing anticipated the idea of using a systemised structural solution that could be used by non-specialist users for architectural manipulation. Advocates of digital-based production argue that through parametric design software geared for the non-specialist, a similar revolution in capacity building in the residential construction sector is available. Timber-based materials are viewed as the most appropriate means by which such broad-based capacity may be delivered.

## 3 A Question of Tolerance

Early attempts to integrate human and mechanical outputs via computer-assisted processes raised questions on the nature of this engagement and its potential ramifications. The ‘M.I.T. Computer-Aided Design Project’ at the MIT Lab, active between 1959 and 1967, sought to evolve machine systems to permit the interaction of human designers and computers in design applications (Cardoso Llach 2015; Ross 1960). On the manufacturing side, they sought to transfer human engagement to an automated and controllable digital process. While the CAD process turned into a complicated definition of mathematical and geometrical codes, the translation of the manual craft operating a milling machine resulted in a complex socio-technical system that demanded new skills and new kinds of craft relocating work shifting from the shop to the programmer’s desk (Cardoso Llach 2015). Today, the interaction of human and machine has not made craft obsolete but has made it accessible to the designer. It has gained new relevance in the production process not only in the translation of design conceptualisation but the capacity to test, verify and adjust the design idea and then deliver it through a CAD/CAM interface. Computer-aided tools enable fully automated controlled machining, to provide tolerances and preciseness previously challenging to produce. This accuracy has allowed the construction of complex timber forms, as witnessed by the ICD/ITKE Research Pavilion 2011, 2015–16 and the robotically fabricated lightweight timber shell of the Landesgartenschau Exhibition Hall 2014 (Menges et al. 2017).

The architectural historian and critic Mario Carpo has questioned how and if the ‘digital revolution’, through its new digital technologies, is significantly changing the way architecture is and would have been designed and made (Carpo 2011). The interplay of technology and tool undoubtedly have shaped new design methods and perspectives, both in the early stages of design and in the fabrication and construction phases. The computer has expanded the capacity for formal manipulation and visualisation. Verification of these formal transpositions may occur in real time, integrating structural and performance considerations. The translations of these are now possible to be extended directly into a manufacturing and fabrication process, with construction strategies able to be tested before committing to delivering architectural output. By way of just one example in its application to timber construction, a critical aesthetic look and structural feature of timber construction is its jointing method. Timber joints play a decisive role in the structural stability of the entire system, as well as in the appearance of the timber system where exposed. Their detailing and delivery have been based on the tacit and explicit knowledge of trade-based craftsmanship and expertise. Digital design and fabrication have provided a capacity for greater precision, accuracy, expressive potential, and resolution to timber joints. This identity is enabled by the millimetric precision allowed by the digital aids in conceptualisation and the manufacturing processes in the transference of design idea to delivery (Garcia 2014). The inverse of this argument is the nature of construction lies in its built output and consideration equally applies to the operative parameters that come to bear once the digital interface has been traversed. What may be conceptualised or suggesting ersatz legitimacy in the digital domain ultimately needs to have an output. This output is subjected to the vagaries of a natural material such as timber, no matter how engineered, the environment, the normative processes of the construction industry, the realities of the site and its tolerances, and the human labour that participates in its delivery. Equally the premise and objectives that underlie the uptake of the digital-design-fabrication trajectory whether explicit or implicit requires consideration in whether it is taken-up, appropriated and modified or marginalised.

## 4 Non-serial Timber Architecture: Three Examples of Digital Timber for Prefabricated Houses

The investigation of such themes may be viewed via the prism offered by a 2008 MOMA exhibition, and the recent interest in 'open-source' architecture. The first two arise from The Museum of Modern Art in New York exhibition entitled 'Home Delivery: Fabricating the Modern Dwelling'. The event, curated by Barry Bergdoll and Peter Christensen, was an attempt to outline the history of the prefabricated house, and in the process display, five prototypes of this housing form to address different characteristics of factory-produced architecture innovation (Bergdoll and Christensen 2008); two used plywood as the primary structural material. The 'Burst*008' beach house, designed by Jeremy Edmiston and Douglas Gauthier and the 'Digitally Fabricated Housing for New Orleans', from the MIT School of Architecture and Planning guided by Professor Lawrence Sass were both designed and fabricated using digital tools, but conceived following opposite approaches to customisation, serial production and preciseness. The third open-source example arose a few years later, in the form of the 'WikiHouse' project which used the similar digital technologies and plywood as its construction material. All three demonstrate the capacity for digital tools to stretch the domain of timber architectures through a mixed community of designers, users, students, fabricators, makers and tinkerers. All three sought to embed the needs of the end-user into an automated design process, using a systemised form of timber construction. 'Burst' sought to do so via an automated bespoke capacity for individual clients, which factored formative manipulation and integrated performance correlations. 'The Housing for New Orleans' project sought to provide a rapid response capacity to natural disasters which took into account architectural design preferences into its generative script using simple construction techniques. 'WikiHouse' sought to devise an open-source digital template that could be manipulated by the end-client directly to produce customised solutions in a defined domain.

## *4.1 Burst*008 House: Customisation and the Bespoke*

'Burst*008' designed by New York-based Jeremy Edmiston and Douglas Gauthier (as *Systems Architects*), had its antecedent in an earlier project, the 'Parish House' (or 'Burst*003') designed by the same team and built in 2005 on the east coast of Australia as a 'holiday retreat'.

This earlier building was an opportunity to investigate the potential presented by integrating digital techniques in design, environmental performance assessment, fabrication and assembly utilising plywood. The challenge was not simply to offer a pallet of predisposed options but to investigate the nature of serial production in the utilisation of computer-aided manufacturing to generate further permutations of response capacity in human-machine interaction. Its premise lay in appreciating and responding to the needs of client and site but purporting the use of an algorithmic approach in generating a design response.

The building is rectilinear, two spaces deep with three-bedrooms and amenities on one side of the long central axis which faces the street and living, kitchen and dining areas on the other with an adjoining external deck facing the rear yard (Fig. 2). The street façade is windowless, with the rear façade floor to ceiling glass. Customisation lay in its programmatic planning and in being elevated 1.5 m above the ground due to local flood levels. Its generative form was in manually defining the external outline of the two short-end elevations and allowing the structural load-bearing CNC-cut 50 mm plywood rib divisions to be parametrically generated responding to the provision of clerestory strip windows, natural light access, and passive ventilation. The ribs form a two-way oblique grid, the intersecting points connected with custom-made, flexible steel X-brackets (Figs. 3 and 4).

As Iwamoto has commented, 'the system is founded in the belief that prefabrication is at the scale of the construction not at the scale of the building' (Iwamoto 2009) and it is at this level that the digital design and digital fabrication nexus needs to be understood. Assembly and installation of digital outputs cannot be digitised, no matter the robustness of the model or the accuracy of the CNC machine, prefabrication is only part of the construction story. The formal articulation of the architecture and the optimisation of the plywood sheets resulted in 1100 non-identical timber sections (as shown in Fig. 4). Although it is argued that prefabrication assembly requires low-skill labour and in this case, architectural students provided some support, the skill set lay not in assembling a perfectly fitted and coordinated set of parts

**Fig. 2** ‘Burst*003’, 2005, on the east coast of Australia: on the left, the view from the rear yard. On the right, view of the undercroft, where the structural system is fully visible. *Source* Gauthier Architects archive [online]. Available at: http://gauthierarchitects.com/work

**Fig. 3** ‘Burst*008’ at the MoMA Exhibition 2008. On the left, end elevation view. On the right, oblique view of the frame. *Source* Gauthier Architects archive [online]. Available at: http://gauthierarchitects.com/work

but in the logistics of having to deal with these parts in on-site realities. The aspect of architectural students not being considered as ‘skilled’ when it comes to digital design and the interpretation of information so produced may also be questioned.

One could argue that they are highly skilled, potentially far more in such techniques than the traditional tradesperson. Regardless, the critique often laid at the architect’s feet in appreciating the nature of construction becomes ever more paramount where digital modelling for fabrication outputs shifts upstream into the

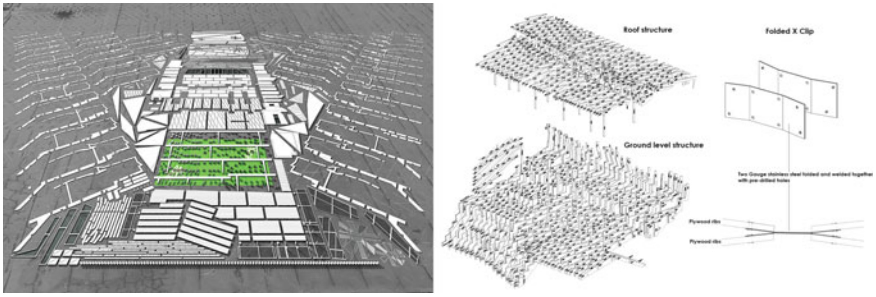


**Fig. 4** ‘Burst’ system. On the left, the components of the kit. On the right, structural components made of CNC manufactured pieces and the X-Clip connector. *Source* Gauthier Architects archive [online]. Available at: http://gauthierarchitects.com/work

design phase. Resolution of the entire system and process is required at the design stage, with tacit knowledge of these types of folded structures still in their infancy in the general construction industry and relatively unknown at the scale of a single residential house. The accuracy requirement of folding structures and the tolerances of the building site are different from those available in the digital environment. By way of example, an issue that manifested itself in both the ‘Parish House’ and the MOMA exhibit lay with the innate lateral instability of planar plywood elements which relies on the connection system to provide rigidity to the structure. Although considered at the design stage, the realities of such issues as constructability—when one attempts to connect architectural design and building directly such shift requires the designer to accept a broader pallet of responsibilities (Buri and Weinand 2011).

The ‘Parish House’ and the subsequent ‘Burst*008 House’ for the MOMA exhibition where the system was further refined, suggest that customisation and optimisation are available via digital means. In formally complex buildings such as the ‘Burst’ projects, the challenge of developing a building system for potential mass consumption which is not embedded into the normative industrial practice of construction has ramifications which go beyond solving the digital design side of the equation.

### *4.2 Housing for New Orleans: We Want a Shotgun House*

The ‘Digitally Fabricated Housing for New Orleans’ by Prof. Lawrence Sass (Principle Investigator, MIT School of Architecture and Planning) in conjunction with MIT researchers, was designed to not only respond quickly to such natural disasters as Hurricane Katrina[2] but also to investigate the potential for design variation

[2]On August 29, 2005, Hurricane Katrina made landfall in New Orleans. It was an extremely destructive Category 5 hurricane that caused catastrophic damage along the Gulf coast from central Florida to Texas, much of it due to storm surge and levee failure.

capacity via interlocking structures, for unskilled site assembly (Sánchez-del-Valle 2011). The predecessor of this experiment is the *Instant House* developed by Sass and Botha (2006) from M.I.T.'s Design Lab, aimed at studying how digital design and fabrication can be employed in an emergency housing scenario (Sass and Botha 2006).

The formal expression or 'styling' of the New Orleans project was the vernacular typology of the 'shotgun house'. Sass chose this traditional form due to it being an identifiable part of a place-bound collective imagination utilising a familiar cultural trope in affording social acceptance of the use of digital tools in housing construction applications (Sánchez-del-Valle 2011). The 'Digitally Fabricated House for New Orleans' represented an opportunity to demonstrate a craft-like experience, open to customisable variation using digital design and fabrication. The timber frame construction of this typology, being one room wide and four rooms long suited the use of 'planar construction' outputs of digital manufacturing from CAD modelling. A characteristic feature of this type is its ornate front porch, a distinctive symbol, and an opportunity for the demonstration of the carpenter's craft; the shotgun house was also the place where carpenters and masons could pass their knowledge and skills, allowing apprentices to learn their trade (Upton and Vlach 1986). The 'Digitally Fabricated House for New Orleans' used digital design and fabrication techniques to display that variation, distinctiveness and personalisation is available and is not limited to prefabrication of repetition (Fig. 5). Its delivery methodology lay in the production of a 3D design model, from which plywood cutting optimisation to suit standard plywood sheet sizes were produced. Flat packed and bundled for assembly by modular componentry, connections of the panels relied on friction-based interlocking sheet members (Sass 2007). Cognisant of the labour implications of on-site assembly, it was built with the help of MIT students, using only rubber mallets. Constructed out of 7000 VNC-cut plywood components, locked together by friction, utilising no nails or screws and requiring little measuring or cutting on the worksite (Fig. 6). With a labour force of four persons, the complete onsite project process took 23 days.[3]

However, as in any prefabrication system, the efficiency of on-site assembly relied on significant upstream design resolution, detailed documentation, checking and verification and pre-planning. The team acknowledged that, for 'smooth' on-site assembly process, it required a considerable time commitment for the CAD modellers. Ostensively as the tasks were going beyond traditional construction documentation as a communication method of design and performance intent, the modellers had to accept the responsibility for tasks normally given over to and the remit of those that follow design in the construction supply chain. They had to engage in the more detailed tasks of consideration for structural integrity, constructability and buildability, resource optimisation, resource planning and logistics. As a prototype, it revealed that further development, integration and refinement was required for many of these CAD-related functions which lay in the upstream domain of design.

[3]The base structure was assembled in 18 days and the white ornamentation components were assembled in 5 days. Data available on http://ddf.mit.edu/news/2014/project-summary.

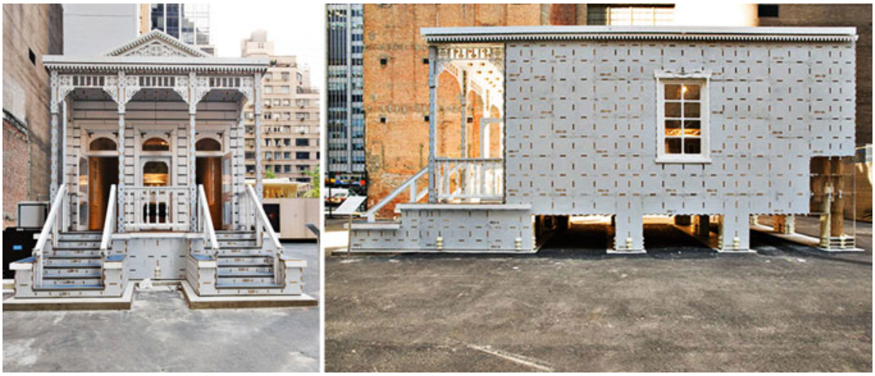

**Fig. 5** The digitally fabricated house for New Orleans at the MoMA Exhibition 2008: front and lateral view. *Source* Professor Lawrence Sass, photo by Suzanne Camarata Ball

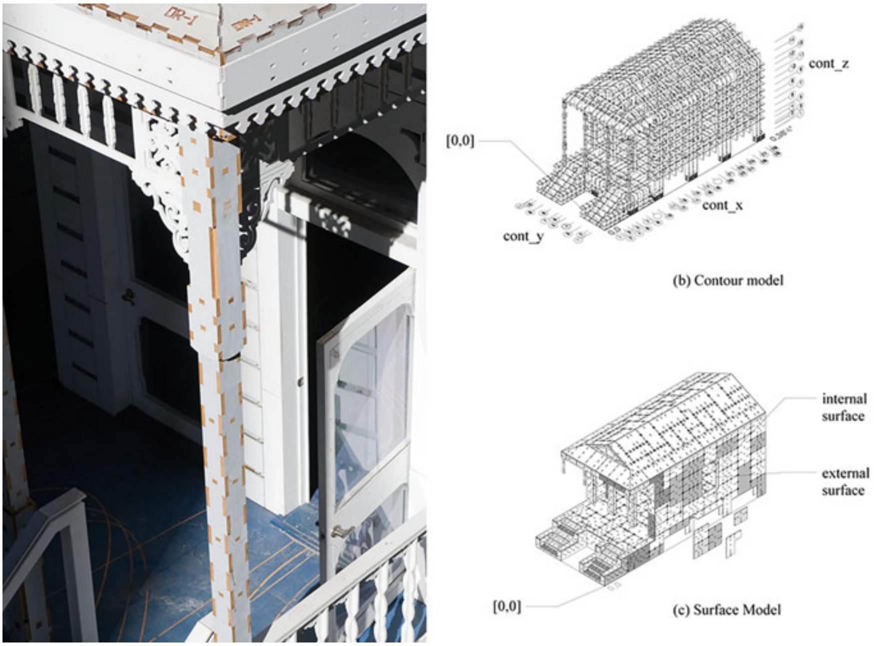


**Fig. 6** The 'Digitally Fabricated House' for New Orleans at the MoMA Exhibition 2008: details of the CNC components of the porch and 3D view of the components. *Source* Professor Lawrence Sass, photo by Suzanne Camarata Ball

The 'Digitally Fabricated House for New Orleans' demonstrated that the capacity of Computer-Aided Manufacturing had challenged the climate of serial production by making possible a process of home delivery with digital fabrication machinery as an alternative to craft and factory-based prefabrication (Fig. 7). In this capacity, it may be


**Fig. 7** The 'Digitally Fabricated House' for New Orleans at the MoMA Exhibition 2008: front view and details of the CNC components of the balustrade. *Source* Professor Lawrence Sass, photo by Suzanne Camarata Ball

considered as a contemporary manifesto of the 'simple technology' envisioned by the architect and urban designer Yona Friedman to give people in difficult circumstances tools and ideas in access to particularising space and facilities (Friedman 2006).

### *4.3 WikiHouse: Open-Source Customisation*

Open-source business models have been put forward as an effective strategy for solving local issues by harnessing collective knowledge and applying this to specific situations (Garcia 2016). The idea of a democratisation of architecture through open-source means and citizen-centred design is not new and may be found in the 'Mobile Architecture' concept of Yona Friedman in the late 50s (Friedman 2006), as well as in the utilisation of automation of the design process in Nicholas Negroponte's research in the mid-70s (Negroponte 1975). One of the most recent manifestations that coalesce these early trends is the 'WikiHouse' project. During a TED talk in 2013, Alastair Parvin, one of the co-founders of the project,[4] argued that built environment design carry a social responsibility that is universal, while architects, by the nature of their protectionist approach, limit their skill set availability to a very small and privileged market sector. The 'WikiHouse' approach advocates for the use of open-source digital-based platforms enabling access to creative commons licensed

[4] The WikiHouse Project was initiated in 2011 by Alastair Parvin and Nick Ierodiaconou of 00 Architects, a London-based design practice, in collaboration with Tav of Espians, James Arthur now with 00 and Steve Fisher of Momentum Engineering.

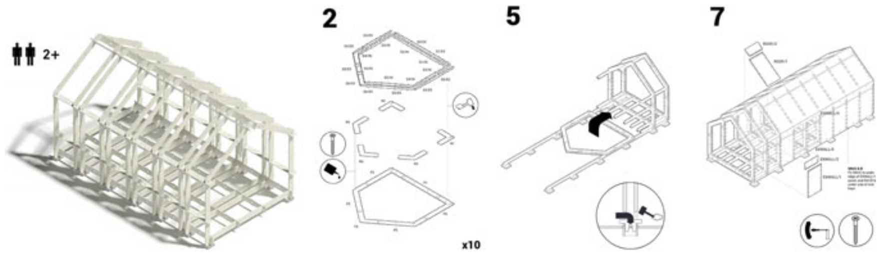


**Fig. 8** ‘WikiHouse’—instructions for the assembly of ‘MicroHouse’, one-bed house type, designed using the WikiHouse building system, initially developed in the UK for European contexts, by 00 Architects. The numbers 2, 5 and 7 refer to different stages of the assembly. Drawings licensed under CC-BY-ND. *Source* WikiHouse [online]. Available at: https://wikihouse.cc/

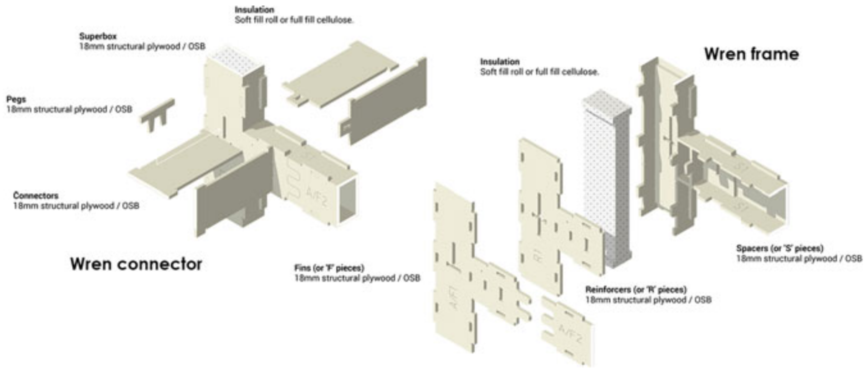


**Fig. 9** ‘WikiHouse’—details of the component ‘Wren’, CNC manufactured using structural-grade timber panel materials developed by 00 Architects. Drawings licensed under CC-BY-ND. *Source* WikiHouse [online]. Available at: https://wikihouse.cc/

information for the construction of houses (Fig. 8). A freely available open-source library of solutions of plans and details of connections (such as the ‘Wren’ connector, Fig. 9) and structural components, applied to timber construction cut using CNC machining, and applicable and modifiable through ‘Google SketchUp’ to anywhere in the world which has access to such resources allows broader access and a shared feedback loop to improve outcomes (Isaacson 2013).

A display of one of the last iterations of the system is ‘WikiHouse 4.0’, designed by 00 Architects in collaboration with Arup and The Building Centre for the London Design Festival 2014. The two-storey prototype, incorporating energy efficiency measures, was built in twelve days by a team of volunteers (Grahame 2014). The engineering consultancy firm Arup also developed for this occasion an open-source heat recovery unit called ‘Open MVHR’, which can be built with 3D printed components and aluminium sheet from beer cans (Mok 2014).

This last iteration (Fig. 10) demonstrates the evolving potential of customisation in incorporating other inputs such as solving local energy-efficiency issues and using

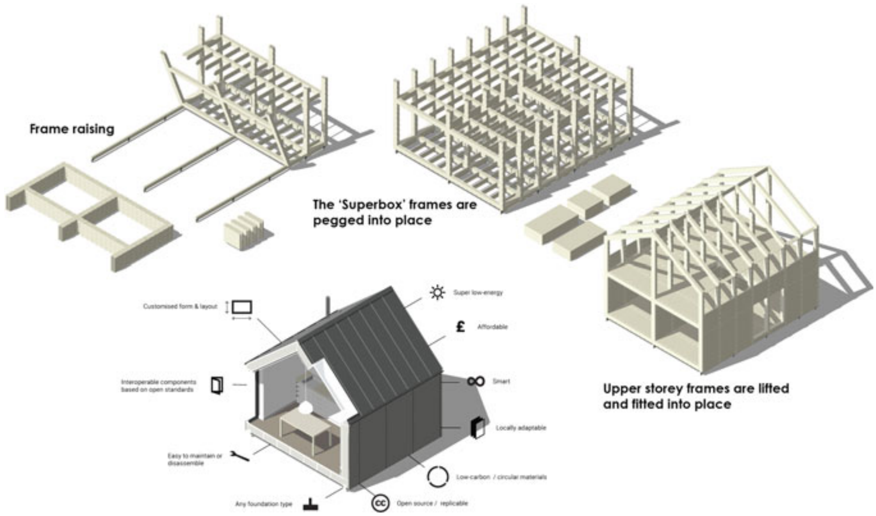


**Fig. 10** 'WikiHouse'—assembly process of the structural system for 1-3 storey buildings, initially developed for European contexts, by 00 Architects. Drawings licensed under CC-BY-ND. *Source* WikiHouse [online]. Available at: https://wikihouse.cc/

locally appropriate recycled materials. Such inputs have a universal cache in accumulating various permutations of particular operative conditions to an adaptable base model to be responsive to that which is local, and which is project specific. However, although open-source web-based generative information permits the expansion of inputs beyond geographic boundaries; its limitations lie within access to the technologies of its containment and resources at hand and at that time (Parvin 2015). Digital platforms and tools may narrow the gap between design creativity, demand for architecture and access to its production, and offer a method to (re)democratise housing design and production (Anderson 2012) but only in terms of those who have access to these tools of production.

## 5 Themes

The three projects offer insight into different modes of interpretation of digital-based transference of design to fabrication. These include such issues as craftsmanship, domains of practice, production, participation and knowledge.

Despite their limitations, the projects presented demonstrate that a process utilising digital-design-to-digital-fabrication techniques opens alternative avenues for kit home production. Leveraging digital platforms, architects can embed parametrically responsive design, engineering simulation, fabrication outputs and implementation into the creative process. Team-based bespoke amalgamations which dissolve through the project development and implementation cycle, a feature of the construction industry, does not afford broader shared knowledge. The view that retention of design thinking and delivery expertise offers competitive advantage lays the construction sector open to criticism in not being innovative and offering low productivity. An alternate view lies in the enabling presented by digital tools and the potential for design lying in a sharing of responsive design solutions. Much debate has passed in professional associations in the construction sector with the advent of building information modelling on the legal and risk ramifications of a single shared digital platform. The collaborative platform afforded by digital communication methods has already established a quasi-open-source platform, albeit contained within a project-based system. However, cloud-based applications such as those that apply in document and workflow management offered by external commercial entities permit utilisation of meta-data for further commercial offerings.

Major barriers exist to such housing propositions as ‘Burst*008’, the ‘Digitally Fabricated House’ and ‘WikiHouse’ as a simple solution for housing. These span such things as access to capital for the investment required to engage in a digitally driven economy, to purchase equipment, education access for computer literacy, the technical knowledge, to operate tools like a CNC router or to customise a 3D model and the ability to navigate the regulatory environments of planning and building compliance. Despite the uncertainties and difficulties in grounding digitally engaged projects, discussion behind their concept is worthy of debate and trial. The building material that satisfies many of the criteria of digital transmutations in housing and lies as the basis of experimentation which is historically accepted, universally understood, accessible and workable is timber and its processed derivatives.

## *5.1 Craftsmanship*

The Oxford English dictionary defines *craftsmanship* as a ‘skill in a particular craft’ or ‘the quality of design and work shown in something made by hand’, its ‘artistry’. It also defines *craft* as an ‘activity involving the skill in making things by hand’. The intent of timber engineering in plywood, for example, is the removal and regularisation of the caprice of natural timber fibres in its grain by flattening and rotating the material. One could argue to what extent the engineering of timber removes the artifice of the craft of understanding the raw material in the manner in which behaves and the extent to which a particular piece can be utilised. Craft, in this scenario, no longer connects knowledge of the material or the responsiveness of the hand (removed from the making) to the nature of the material’s properties. *Crafted* takes on a figurative form of the verb, not in the nature of craft as a noun—but in giving primacy to the process. Does digital design to fabrication then remove the acts of craft and craftsmanship? David Pye and Malcolm McCullough (Pye 1978; McCullough 1998) have argued for a reconceptualisation of digital tools as an aid to the artisanal tradition of designers. Digital means of design and fabrication both reconnect and extend this tradition. The projects each display facets of this approach, equally they offer an insight into the questions around the political economy of design and the sociological and economic systems that come to bear within architecture and the construction industry.

'Burst*008' presented a prototype, an outline for a potential system for mass customisation and variation responsive to site and program, through formal architectural manipulation. Its offer was to provide a quasi-parametric design tool for flat-pack production not necessarily a fully resolved structural building solution. In this, the hand of the constructor was still required, not only to assemble a predetermined kit of parts but to have knowledge of how to bring the system together into a cohesive whole. As with most timber-based folded structures, the formal complexity of the timber planer elements relied on the node plate connectors to bring structural stability to the system. The knowledge required to achieve this, lay as with most building construction, in the constructability skill of the assembly team—in the craft of knowing how to coordinate the process and how to put things together.

'Digitally Fabricated Housing for New Orleans' attempts to replicate, by mechanical means, a signature or hand of the traditional craftsperson. It recognises the value of the hand and its local variation and interpretation of timber construction. Digital design and fabrication permit the recording of a local vernacular and the capacity to replicate or reinterpret this into an affordable recognisable and accessible typological output. By doing so, it places a value on the local building tradition and argues that digital design and fabrication offers the means to retain a local and culturally significant building design response that may be applied even in extreme conditions such as those arising from natural disasters such as Hurricane Katrina.

'WikiHouse' harks back to the tradition of architectural pattern books where template designs were shared and made available to replicate these archetypes for implementation to a broad audience and geographic location. The crafting lies in the process of interpretation of the template and the development of this template in open source design platforms as customisable and adaptable uptakes framed within the bounds of the template. As with architectural pattern books, the use of the template does not preclude local variation and adaption but serves in part as an enabling mechanism. The 'WikiHouse' approach replicates the traditional pattern book by presenting itself as a reference where the initial underpinning design has been established remote from the source of application. Unlike the intent of the original pattern book, it accepts the implementation of the pattern in itself, which becomes a potential source of development and refinement through open-source means.

### *5.2 Domains of Practice*

The projects provide insight into differing perspectives on how digital design and fabrication can operate at various domains of practice, in the nature of the architectural client, design development and testing, within varying commercial realms and at vastly different scales of output.

A commonality of theme in the three projects is the argument for digital-based production mechanisms is in its universal application in the provision of accessible design thinking, through a globally comprehensible communication means delivered via a portable means of controlled production. The residential client may be bespoke (Burst), tailored to a specific community (New Orleans House) or a customisable prêt-à-porter (WikiHouse). The internet offers the architect not to be geographically bounded nor at the mercy of varying capacities of building knowledge, labour, practice, and technologies. Production may equally operate as a singular typological output, customisable on a mass scale or generically applied through mass production or adapted through the world-wide-web of tinkerers. The projects, therefore, are representative of the optimism of digital design to fabrication and its usefulness in its flexibility to deal with scale in residential applications. This local-to-global scale of engagement is facilitated in no small part not only due to the digital aspect of process application but also via the utilisation of embedding a material that is universally familiar and accessible. Timber and its derived products fulfil a critical role in these investigations into contemporary technology-based solutions to a diversity of client for responsive residential building production.

This digital-based form of design and production offers access to another kind of client, not defined as the end user but as an active agent, operating further along the supply chain and directly involved building. Once design and fabrication are directly linked, it offers the capacity for those involved in fabrication not to be de-skilled or re-skilled facilitators of the execution process but to be active agents in the management of design. This shift is evident in commercial building procurement where the expertise of the builder is valued by the client and early contractor involvement up the supply chain is becoming the norm. Just as it is argued that digital design to fabrication reconnects the designer to the construction process, it equally offers passage for the contractor to be an active agent in design.

The projects, therefore, are representative of design-driven innovation where the seed of the innovation lies within the domain of a design intent output. The projects are indicative of designers adapting to the availability of design tools and fabrication systems to promote design solutions to conventional design problems. They also represent the dilemma and limitations that are structural from an industrial perspective, for regardless of the rhetoric of the possibilities of digital processes to take advantage of the scale of application they require capital and investment from broader industry sectors beyond the remit of the designer. Timber offers an accessible and cost-effective entrée, for the three project prototypes—they are, however, still awaiting uptake within the broader construction industry. Materials and technology do play a part in the story, robotic 3D printing of concrete or robotic automation in masonry offer benefits to the manufacturer and the constructor which are commercially transferable to the commissioning agent. The efficiency of the timber platform frame and its continued use in prefabrication, catering to an industrial sector characterised by a fragmented supply chain, is an embedded system of residential building practice where substantial innovation is difficult to penetrate.

This does not devalue the opportunities presented by the digital environment for residential applications. The great advantage of these systems is in the developmental sophistication of the tools to be increasingly responsive to the intuitive nature of architectural design conceptualisation. Such tools also permit the rapid investigation of multiple and simultaneous design investigation to nth-degrees of complexity that may be immediately checked via parametric inputs. The connection to fabrication systems facilitates rapid prototyping and testing, tapping into an iterative process for performance improvement and client ratification.

### *5.3 Kit Home Production*

The three examples can be interpreted as a demonstration of what prefabricated housing can achieve by mining the possibilities of the computer. The architects, to varying degrees engaged in architectural form making, share a larger interest to develop a system of digital-design-fabrication production that may be applied in the single-family housing sector utilising timber as its means of delivery.

Tailor-made production systems can be made broadly available through a network of shared knowledge. Recently, new user-friendly software tools, such as 'Grasshopper 3D' and its plug-ins, which define the geometry of structures parametrically, form a large and shared database of possible solutions and details. Negroponte's argument for the nexus between the human designer and the computer, as designer, is reignited (Negroponte 1975). Democratising the production of architecture is mirrored in broad-based access to digital tools and integrating these into the supply chain or in shifting the links in the supply chain. Curiously, the use of digitally-based technologies has looked to a very traditional building material to advance its cause in the construction industry—timber, timber engineered and timber-based products. Kit home production has shifted from a factory packaged export with limited optioning to a locally enabled production method that is customised to a particular client and site requirements. In part, this has arisen due to the means of production being broadly disseminated, via CNC machines, the advent of sheet-based timber products of known behavioural characteristics and properties and the development of software tools that embed professional knowledge for the layperson.

Digital tools present a further permutation to the do-it-yourself (DIY) building culture characteristic of the Anglosphere (see Peters 1989 for America and Dingle 2000, for Australia) but equally evident in those manifestations of self-resilience, need or desire of many locales. This DIY approach through digital distribution offers access to alternative methods of design realisation and construction, where one may engage commensurate with one's knowledge base or interest. This does not mean that it removes the aspect of privileged knowledge, but both adds and provides access to design conceptualisation and delivery as a kit of parts. The architect may still be required to provide the skills commensurate with the profession, however, in the post-representational space of the digital environment one either acquires or engages the expertise required by the translation tools of the digital environment—3-D modelling, algorithm editors, coding.

The kit, as used in the project examples where material behaviour is controlled using plywood and in its parametric conditioning of performance opens the opportunity for a wider audience of enablers, participants, and assemblers. Digital design to fabrication in its predetermined and coordinated components and its application of simplified and consistent connection systems reduces the reliance on the craftsmanship of trade-based experts, such as carpenters or metalworkers. Such tools are extending to the building services sector, where digital means permits off-site prefabrication to lower skilled on-site tradespersons (Korman and Lu 2011). For this to be effective, however, digital design to fabrication requires preciseness and unpredictability and deviation from the predetermined path to be removed. To utilise the digital aspect of design, it is best to minimise the vagaries of the material and limit the capacity of the DIY participant to intervene. For the system to operate, its constituent parts and the process by which these parts come together are best when they are predictable and maintained for as long as possible in the environment of the digital-design to fabrication domain. Where transference ultimately occurs, as with any prefabricated building system, axiomatic structures of communication, and comprehension come to play by necessity. Industrial engineered timber and digital-based building production therefore retains the specific material culture of timber and adds another chapter to evolving building practice.

### *5.4 Participation as Apprentice*

The advent of the platform frame and its dissemination was a response to capacity building using elementary components, simply and cheaply connected without the requirement for skilled labour. The system made building construction accessible to a far broader labour force not bounded by trade-based knowledge. It also responded to underdeveloped supply capacity both in the availability of materials, labour and in the maturity of a construction sector, in meeting demands of land development. The iteration of timber frame prefabrication required another link to be added to the supply chain. Efficiencies in this system of production lay in minimising complexity and encouraging repetition and systematisation. Cost efficiencies in material and labour and reduction in construction time in the highly competitive single-family home residential market sector encourages standardisation and limits formal design agency to manipulation of the 'face' of the object. One may, therefore, speculate on the rise in interest in the digital design and digital fabrication nexus. It offers a potential contraction of the supply chain by linking design directly to a fabrication output, by embedding the translation interface into the 'software', without the need for an additional construction compositor. It, therefore, presents an opportunity for some formal but limited design manipulation but endless repetition. It, on the other hand also presents an opportunity for mass customisation, high design complexity and performance integration.

The three projects all stake a claim for the applicability of their respective systems in the use of non-skilled workers. All systems it is argued can be assembled by a small group of people with limited construction experience; the lightness of timber allows that. An argument that may be equally made for the traditional timber stud framed building. This feature of labour efficiency has been one of the mainstays of this form of construction which has permitted the longevity of this ‘stick-based’ system in domestic construction in those economies that have embraced the timber frame. Digital production does not alter this, assembly system methodology however does. As suited as it is to the potential removal of the reliance of tacit construction knowledge, and thereby locates participation as apprentice, it also facilitates the removal of the trade apprentice as participant. For all its advocacy for an opening of access to non-skilled labour in the domestic construction process, it also presents another method of labour deskilling in the domestic construction sector.

The ‘Parish House’ and the M.I.T. MoMA project were built in part with the assistance of architecture students, therefore, exemplifying the robustness of the building systems for unskilled labour assembly. The projects exist as points in time examples of the digital pathway in construction and equally as research investigations and prototypes. In these terms reflecting a research method of the utilisation of the academic environment as test beds for building research practice before potential adoption by industry.

The case for being unskilled required some qualification—this may have been the case as the system removes the necessity of expertise in timber carpentry. However, such students potentially may have been overqualified as workers for the manipulation of digitally enabled communication platforms, as well as the interpretation of 3D drawings and optimisation of complicated plywood shapes. By doing so, they were anything but unskilled. Two German words are used to describe the nature of experience; *Erlebnis* in the participation of a memorable event—to have an experience and *Erfahrung,* to obtain a skill—to gain experience. Both describe the nature of experience that is used in student participation of digital supported learning such as promoted by the ‘Parish House’ and the MIT MOMA project. However, they overlook *Fähigkeit*—the capabilities and abilities that students possess in being digitally literate. In its open-source approach, the ‘WikiHouse’ project, presents alternate opportunities for participation in all three approaches to the engagement of experience.

The aspect of the use of unskilled labour is reflective of an industry shift in cost management arising in those economies where the balance of project cost lies on the labour side of the ledger rather than in the costs of materials or equipment. Such profiles further seek to leverage returns in reducing construction time as much as possible. The digital-design to fabrication process, therefore, is seductive for those construction economies that seek to minimise labour cost or reduce construction time. Capital investment in tooling is set against the costs associated with production processes reliant on skilled labour or where substantial reduction of on-site time may arise from such investment. In those economies where construction labour costs are lower than material and equipment, there is little incentive on an industrial scale for the capital investment and training required regardless of the potential low-entry investment offered by the digital environment. In such economies, the percolation of this type of construction innovation may take longer to have an impact locally, even though these economies may offer such services externally.

## 5.5 Cross-Disciplinary Knowledge and 'Simple Technology'

Human-machine interaction offers an avenue to embed building performance criteria into customisable components. Digital tools facilitate the envisioning of complexity, both formally and in performance terms, but also provides the means for it to be simplified, analysed, managed, and delivered. The outputs may be packaged to suit an industrially mature construction environment or market sectors that would benefit from simplicity or opt for more traditional means of transposition. Mass-customisation in timber-based architectures leverages these advantages to enable Slessor's idea of 'uniqueness' as an economic possibility beyond repetition and the 'creative capabilities of electronics' (Pine 1993) to much broader-based applications. The question lies in the capacity of digital design to digital fabrication to offer a high degree of customisation, formally and architecturally, in site specificity, and in performance criteria, while integrating resource efficiency and rapid deployment capacity.

However, one of the key features of the construction industry is that it has a fragmented supply chain characterised by small businesses and independent contractors. This structural industrial form presents both challenges and opportunity in both training and investments across all market sectors to embrace the offerings of digital environments fully.

Digitally-based design and analytical tools permit the harnessing of the innate properties of timber and timber-based products for the form making capacity offered by the digital design environment. The elastic properties of wood may be utilised in rib shell structures or weave configurations taking advantage of the redundancy of the weave as a system. The strength characteristics offered by glue-laminated plywood and shape profiling lend itself to applications from traditional load-bearing arrangements to folded structures (Buri and Weinand 2011). The environmental and economic advantages of timber-based products coupled to its low-skill labour utilisation further weigh-in for the continued relevance of timber as a material in emerging parametric design and digital fabrication methods.

It could be argued that the three houses exemplify the use of digital tools to offer access to intellectual capital and information exchange via a construction material that, in its ancient configuration, traditionally circumvented formally driven social structures.

## 6 What's Meant to Be Will Always Find Its Way

The ubiquity of technology has altered material culture, with capacity building undergoing exponential expansion to the possibilities and permutations of its application. It could be argued that the three projects exemplify the potential of digital tools to offer access to intellectual capital and information exchange via a construction material that, in its ancient configuration, traditionally circumvented formally driven social structures. Is there potential for a wider spectrum of the social structure of building to present itself? The linear supply chain of building is potentially disrupted—where the direct links of design conceptualisation are integrated with fabrication and assembly method. A challenge is presented to the designer on several fronts as it not only requires knowledge of construction but also requires the designer to participate in the delivery of building. Equally, it presents the constructor with a further opportunity to move up the supply chain and into the conceptualisation and design production phase.

In utilising digital tools in the service of architecture using a natural material like timber; one still confronts the unpredictability of such materials. Analysis and simulation take one just so far until one faces a requirement for tacit material and construction knowledge. The three projects discussed here have used plywood as the primary structural material, in this use of engineered timber one is further removed from an appreciation of natural material properties. However, in terms of building knowledge, the use of digital design and fabrication in timber still presents a Janus-like opportunity, it permits one to look to the future while simultaneously arguing for an appreciation of the lessons of the past that are embedded in an understanding of tacit knowledge of building.

Furthermore, timber whether engineered or otherwise lends itself in the digital-design to fabrication nexus of production scale. It can equally be utilised for mass production, mass customisation or the bespoke. The three examples engage with the nature of scale and production method. They offer a capacity for a mixed community of designers, of student leverage and engagement, of manufacturers, fabricators, assemblers and tinkerers operating in residential building supply, be it as a generic globally applied template, as an enabler to a specific community of practice or as a customisable bespoke singular product.

Digital-design-to-digital-fabrication does not negate appreciation of materiality. It highlights the difference between point-in-space robotic construction of masonry or sprayed concrete and timber, where the behaviour of the material and its connections still retain the input of the hand. Intuitive and tacit knowledge remains, tied to the stick construction assembly method of timber, whether it be in the adjustment of the slip joint connections of a timber gridshell, the rubber mallet and crowbar of the 'Digitally Fabricated House for New Orleans' or 'WikiHouse' or the node connections of 'Burst*008'.

The saying *What's meant to be will always find its way* is often quoted as an aphorism for a statement of will and applied intent. The inevitability of the digital age and its will of propulsion, the ubiquity of the internet of things will eventually find an avenue for the implementation of digital-design-fabrication to be endemic in the timber construction sector. However, the saying equally may be applied to the concept of time. Perhaps the applicability of a traditional construction material like timber remains timeless and a contemporary construction solution equally suited to the digital age. *What's meant to be will always find its way*.

**Acknowledgements** The catalyst for much of the thoughts outlined in this article arose through numerous discussions with our colleagues at the University of Melbourne, Prof. Paolo Tombesi has been a feature of many of these conversations, for which we are appreciative. Some of the information on 'Burst' House*003 and *008 are gathered from a research project on the industrial potential of digital fabrication technologies commenced by the late University of Melbourne academic, Professor Bharat Dave, and concluded by Paolo Tombesi—chief investigator, Blair Gardiner—investigator, Sofia Colabella—research assistant; (Tombesi et al. 2016).

## References

Anderson C (2012) Makers: the new industrial revolution. Cornerstone Digital, Rushden

Bergdoll B, Christensen P (eds) (2008) Home delivery: fabricating the modern dwelling. The Museum of Modern Art, New York

Buri H, Weinand Y (2011) The tectonics of timber architecture in the digital age. In: Kaufmann H, Nerdinger W (eds) Building with timber paths into the future. Prestel Verlag, Munich, pp 56–63

Cardoso Llach D (2015) Builders of the vision: software and the imagination of design. Routledge, London

Carpo M (2011) The alphabet and the algorithm. The MIT Press, Cambridge MA

Dangel U (2016) Turning point in timber construction: a new economy. Walter de Gruyter GmbH

Davies C (2005) The prefabricated home. Reaktion Books, London

Dingle T (2000) Necessity the mother of invention, or do-it-yourself. In: Troy P (ed) A history of European housing in Australia. Cambridge University Press, Cambridge, pp 57–76

Falk A (2005) Architectural aspects of massive timber—structural form and systems. Doctoral thesis Luleå University of Technology, Sweden. https://www.diva-portal.org/smash/get/diva2:999695/FULLTEXT01.pdf

Falk A (2013) Cross-laminated timber: driving forces and innovation. In: Cruz (ed) Structures and architecture: concepts, applications and challenges. Taylor & Francis Group, London, pp 511–518

Freeman C (1982) The economics of industrial innovation. Francis Pinter, London

Friedman Y (2006) Pro domo. Actar, Barcelona

Garcia M (ed) (2014) Future details of architecture. Architectural design (AD) series. Wiley, New Jersey, pp 14–25

Garcia M (2016) Architectural patents and open-source architectures: the globalisation of spatial design innovations (or learning from 'E99'). In: Architectural Design (AD), vol 86, no 5. Wiley, New Jersey, pp 92–99

Giedion S (1941) Space, time and architecture: the growth of a new tradition, 1st edn. Harvard University Press, Cambridge

Grahame A (2014) How to build your own sustainable house. In: The Guardian, 23 September https://www.theguardian.com/sustainable-business/2014/sep/23/build-own-sustainable-eco-house-wikihouse

Herbert G (1984) The dream of the factory-made house. Walter Gropius and Konrad Wachsmann. The MIT Press, Cambridge MA

Isaacson B (2013) WikiHouse democratizes design for inexpensive, easily built homes. In: The Huffington Post, 1 March https://www.huffingtonpost.com.au/entry/wikihouse-design-inexpensive-homes_n_2790860

Iwamoto L (2009) Digital fabrications: architectural and material techniques. Princeton Architectural Press, New York

Korman T, Lu N (2011) Innovation and improvements of mechanical, electrical and plumbing systems for modular construction using building information modelling. In: Proceeding of the architectural engineering conference, Oakland, California, pp 448–455

McCullough M (1998) Abstracting craft: the practiced digital hand. The MIT Press, Cambridge, MA

Menges A, Schwinn T, Krieg OD (eds) (2017) Advancing wood architecture: a computational approach. Routledge, London

Mok K (2014) WikiHouse: open source sustainable house designs that anyone can build. In: The New Stack, 1 Oct

Negroponte N (1975) Soft architecture machines. The MIT Press, Cambridge MA

Parvin A (2015) An open manifesto for housing, https://medium.com/@AlastairParvin/an-open-manifesto-for-housing-a56cf4eed2a1

Peters T (1989) An American culture of construction. Perspecta 25:142–161

Pfammatter U (2008) Building the future: building technology and cultural history from the industrial revolution until today. Prestel, London

Pine BJ (1993) Mass customization: the new frontier in business competition. Harvard Business School Press, Boston

Pye D (1978) The nature and art of workmanship. Cambridge University Press, London

Ross DT (1960) Computer-aided design: a statement of objectives. Technical memorandum, MIT Electronics Systems Laboratory. http://images.designworldonline.com.s3.amazonaws.com/CADhistory/8436-TM-4.pdf

Sánchez-del-Valle C (2011) Digital craft, design and the work of Lawrence Sass. Int Rev Afr Am Art 23(3):37–40

Sass L (2007) Synthesis of design production with integrated digital fabrication. Autom Constr 16(03):298–310

Sass L, Botha M (2006) The Instant house: a model of design production with digital fabrication. Int J Archit Comput 4(4):109–123

Smith M (2008) Associative design in fabrication. In: Kolarevic B, Klinger K (eds) Manufacturing material effects: rethinking design and making in architecture. Routledge, New York

Sprague PE (1981) The origin of balloon framing. J Soc Archit Hist 40(4):311–319

Tombesi P, Gardiner B, Colabella S (2016) Is conventional knowledge enough? In: Chien S et al (eds) Living systems and micro-utopias: towards continuous designing. Proceedings of the 21st international conference of the association for computer-aided architectural design research in Asia CAADRIA 2016, pp 871–880

Upton D, Vlach JM (1986) Common places: readings in American vernacular architecture. University of Georgia Press, Athens